Tesis Doctoral

Personal Health Trajectory Framework: Un paradigma para el desarrollo de software sobre la trayectoria de salud

Francisco Javier Rojo Martín

Programa de Doctorado en Tecnologías Informáticas (TIN)

Con la conformidad de los directores: Dr. D. Juan M. Hernández Núñez y Dr. D. José Manuel García Alonso.

Esta tesis cuenta con la autorización del director/a y coodirector/a de la misma y de la Comisión Académica del programa. Dichas autorizaciones constan en el Servicio de la Escuela Internacional de Doctorado de la Universidad de Extremadura.

2023

A mi familia, por hacerme ser quien soy.
A mis amigos y amigas.
Al grupo Quercus y a SPILab por brindarme la oportunidad de desarrollar mi carrera científica, así como haber confiado e invertido tanto tiempo en mi desde el primer momento.
Y por último y no menos importante, a mis directores, Juan Hernández y Jose García-Alonso, por haberme guiado a lo largo de todo el camino y hacerme crecer en lo profesional y lo personal.

Gracias.

Institutional Acknowledgements

I would like to acknowledge the support provided by the following institutions during the completion of this thesis:

- To the Ministry of Science, Innovation and Universities of the Government of Spain, for the Formación del Profesorado Universitario (FPU) grant, achieved in the 2019 call, with code FPU19/03965.
- To the Department of Economy and Infrastructures of the Regional Government of Extremadura and the European Regional Development Fund (FEDER) through the aid to groups GR18112.
- To the Department of Economy, Science and Digital Agenda of the Government of Extremadura and the European Regional Development Fund (FEDER) through the aid to groups GR21133.
- To the Ministry of Science, Innovation and Universities, the State Agency and Research and the European Regional Development Fund (FEDER) through the projects RTI2018-094591-B-I00 and PID2021-124054OB-C31 (MCIU/AEI/FEDER, EU).
- To the IB18030 project co-funded by the Department of Economy and Infrastructure of the Government of Extremadura and the European Regional Development Fund (FEDER).
- To the projects 00445-4IE-4-P and 0499_4IE_PLUS_4_E co-financed by the European Regional Development Fund (FEDER) through the Interreg V-A Spain-Portugal Program (POCTEP) 2014-2020.

I would also like to thank with great effusiveness all the support offered by the Quercus Software Engineering Group (Quercus SEG) of the University of Extremadura and the SPILab laboratory.

Personal Acknowledgements

In order to improve the mind, we ought less to learn, than to contemplate

Rene Descartes

Finally, after so long, I am at this point where I reach the final stretch of the doctoral thesis and it is time to look back, remember all the moments lived and thank all those who made this path much easier and enjoyable.

First of all, I would like to thank my directors, Juan and Jose, for giving me the opportunity to carry out this doctoral thesis within the Quercus group and the SPILab laboratory. To Juan again, for having thought of me to be part of the group when I was only a second year undergraduate student. To Javi Berrocal, because he was the first to bet on me to give me a position in the university and to hire me for one of his projects. To Juanma, for having been part of the way and for having helped me with his knowledge to achieve many of the merits that today are part of my curriculum.

I would also like to thank the rest of the academic community, all the people that the academy has allowed me to meet over the years and who have helped me along the way. It is time to thank those with whom I have worked more in my day to day. To all the colleagues who have accompanied me since I started in the world of research, when I was still an undergraduate student, until now. To those I have met when I started working in the laboratory after finishing my degree and in which I have developed my master thesis and my doctoral thesis.

In particular, I would like to thank the members of the group "SPILab Cafe y copas", with whom I have enjoyed so many good moments inside and outside the laboratory. And inside of this group, I would like to thank Sergio Laso, Daniel Garcia, Javier Romero and Andres Ventura. The latter joined later, but he knew how to catch up with us quickly and be one more in our nightly escapades to the Fontana on Thursdays.

I feel the need to give a special mention in this part of the acknowledgements to Javier Romero, former student of the Final Degree Project, later lab partner and student of the Final Master's Project, and now friend who has helped me especially along the way since he arrived. He is one of the people who have helped me the most along the way, knowing how to listen to me and supporting me in the most difficult moments.

I also want to thank my friends in the village for all those moments that have helped me to disconnect from the working world and its problems. All those barbecues at the country house. Those night outings to the Terraza and the Petril or the afternoons of cars and coffee. Above all, taking into account that this thesis has been developed at a complicated time for the general population, as has been the Covid pandemic. All the health problems of relatives or acquaintances, all the stress generated by not being able to leave home, has been much more bearable thanks to the help of all of them. Therefore, I would like to list, at least, the names of some of the friends who have been most present throughout this period: Joshua, Michelle, David, Fran and Esther.

Before coming to the end of these acknowledgements, I would also like to thank all those people who, during my stay at the University of Florida, helped me to make those three months much more bearable. My parents and family, who tried to make me feel close to home even though we were miles apart. To the friends who came to visit me in New York and made that week one of my best experiences in the United States. To friends like Michelle who, despite not being able to come see me, made me feel like we were together at all times. To Jose and Adrian, who made those last weeks in Gainesville and Orlando more enjoyable, organizing everything we were going to visit, including parts of Florida that were unknown to me and we discovered together. And, of course, to Mindy, Shadia and Sumi, and especially to the latter, for having made those three months in the United States much more bearable, for having encouraged me to continue improving professionally and growing personally, for having encouraged me to never settle when something is not enough and for having made me believe in my value and that many times we can achieve much more than we expected if we believe in ourselves. For this and much more, I am glad to have made that stay in the United States that I was so afraid of at the beginning. Not only did I find a supervisor for my stay, but I found a person willing to help me in whatever I need, even after the stay. Thank you very much from the bottom of my heart, Sumi.

And like everything in this life, the best part always comes at the end of all things. And that's why I wanted to save this last part of the thanks for my family. For my parents, Ana and Javi, and for my brother, Alejandro. They have been the ones who have helped me get here and who have managed to keep me on track in all those difficult occasions when it seemed that I would not find any other way to continue than the exit. And also to my partner, Gemma, for coming into my life in the last stages of this journey and helping me give that final push I so desperately needed to finish the journey.

Now that it seems that my life is detached from academia with the completion of my doctoral thesis, and I do not know if I will ever return to this world of research and university teaching, I look back with nostalgia at the road I have traveled and I can assure you that I do not regret having walked it.

For all this, and for much more that I could not list in these pages, thank you.

——————— o ———————

Por fin, después de tanto tiempo, me encuentro en este punto en el que llego a la recta final de la tesis doctoral y toca mirar atrás, recordar todos los momentos vividos y agradecer a todos aquellos que hicieron de este camino algo mucho más fácil y ameno.

En primer lugar, me gustaría agradecer A mis directores, Juan y Jose, por haberme dado la oportunidad de realizar esta tesis doctoral dentro del grupo Quercus y del laboratorio SPILab. A Juan de nuevo, por haber pensado en mi para formar parte del grupo cuando tan solo era un estudiante de segundo de grado. A Javi Berrocal, porque él fue el primero en apostar por mi para darme un puesto dentro del universidad y contratarme por uno de sus proyectos. A Juanma, por haber formado parte del camino y haberme ayudado con sus conocimientos a alcanzar muchos de los méritos que hoy forman parte de mi curriculum.

También me gustaría agradecer al resto de la comunidad academica, a todas las personas que la academía me ha permitido conocer en estos años y que me han ayudado en el camino. Es el momento de agradecer a aquellos con los que he trabajado más en mi dia a dia. A todos los compañeros que me han acompañado desde mi inicio en el mundo de la investigación, cuando aún era un estudiante de grado, hasta ahora. A aquellos que he conocido cuando comencé a trabajar en el laboratorio tras finalizar el grado y en el que he desarrollado mi tesis de máster y mi tesis doctoral.

En especial, me gustaría agradecer a los miembros del grupo “SPILab Cafe y copas”, con los que tantos buenos momentos he disfrutado dentro y fuera del laboratorio. Y dentro de este grupo, quiero agradecer a Sergio Laso, Daniel Garcia, Javier Romero y Andrés Ventura. Este último se unió más tarde, pero supo cogernos el ritmo rápido y ser uno más en nuestras escapadas nocturnas a la Fontana los jueves.

Cobra en mi la necesidad de darle una especial mención en esta parte de los agradecimientos a Javier Romero, antiguo alumno del Trabajo de Fin de Grado, posteriormente compañero de laboratorio y alumno de Trabajo Fin de Máster, y ahora amigo que me ha ayudado especialmente a lo largo de todo el camino desde que llegó. Es una de las personas que más me han ayudado en todo este camino, sabiéndome escuchar y apoyandome en los momentos más dificiles.

También quiero agradecerles a mis amigos del pueblo todos esos ratos que me han servido para desconectar del mundo laboral y de sus problemas. Todas esas barbacoas en la casa de campo. Aquellas salidas nocturnas al Terraza y al Petril o las tardes de coches y café. Sobretodo, teniendo en cuenta que esta tesis ha sido desarrollada en un momento complicado para la población en general, como ha sido la pandemia de Covid. Todos los problemas de salud de los familiares o conocidos, todo ese estres generado por no poder salir de casa, ha sido mucho más llevadero gracias a la ayuda de todos ellos. Por ello, me gustaría listar, al menos, los nombres de algunos de los amigos que más presentes han estado en todo este periodo: Joshua, Michelle, David, Fran y Esther.

Antes de llegar al final de estos agradecimientos, también quiero pararme a agradecer a todas aquellas personas que, en mi estancia en la Universidad de Florida, me ayudaron a que esos tres meses fuesen mucho más llevaderos. Mis padres y mi familia, que trataron de hacerme sentir cerca de casa aunque nos separasen muchos kilometros. A los amigos que vinieron a visitarme a Nueva York e hicieron de esa semana una de mis mejores experiencias en Estados Unidos. A amigos como Michelle que, a pesar de no poder venir a verme, me hizo sentir como si estuvieramos juntos en todo momento. A Jose y Adrian, que hicieron más amenas esas últimas semanas en Gainesville y Orlando, organizando todo lo que ibamos a visitar, incluyendo partes de Florida que eran desconocida para mi y descubrimos juntos. Y, por supuesto, a Mindy, Shadia y Sumi, y en especial a este último, por haber hecho de esos tres meses en Estados Unidos algo mucho más llevadero, haberme animado a continuar mejorando en lo profesional y crecer en lo personal, haberme animado a no conformarme nunca cuando algo no es suficiente y haberme hecho creer en mi valor y en que muchas veces podemos conseguir mucho más de lo que espearamos si creemos en nosotros mismos. Por esto y mucho más, me alegro de haber realizado esa estancia en Estados Unidos que tanto miedo me daba en un inicio. No solo encontre un supervisor para mi estancia, sino que encontre a una persona dispuesta a ayudarme en aquello que necesito, incluso después de la estancia. Muchas gracias de todo corazón, Sumi.

Y como todo en esta vida, la mejor parte siempre llega al final de todas las cosas. Y es por eso que he querido guardar esta última parte de los agradecimientos para mi familia. Para mis padres, Ana y Javi, y para mi hermano, Alejandro. Ellos han sido quienes me han ayudado a llegar aquí y quienes han conseguido mantenerme en el camino en todas esas dificiles ocasiones en las que parecía que no iba a encontrar ninguna otra forma de continuar que no fuese la salida. Y también a mi pareja, Gemma, por llegar a mi vida en las últimas etapas de este camino y ayudarme a dar ese empujón final que tanto necesitaba para terminar el camino.

Ahora que parece que mi vida se desvincula de la academia con la finalización de mi tesis doctoral, y que no sé si algún día volveré a este mundo de investigación y docencia universitaria, miro con nostalgia el camino recorrido y puedo asegurar que no me arrepiento de haberlo recorrido.

Por todo esto, y por mucho más que no podría enumerar en estas páginas, gracias.

Resumen

Dada la globalizacion de los últimos años, cada vez es más común que las organizaciones tiendan a ofrecer servicios de manera conjunta con otras organizaciones del mismo ámbito. Precisamente el ámbito de la salud es uno en los que que cada vez se tiende a ofrecer más este tipo de servicios. Una de las razones es el cambio de paradigma que están sufriendo las instituciones sanitarias hacia servicios centrados en los propios pacientes. Por ello, cada vez es más frecuente oír hablar de la transición de los actuales sistemas sanitarios centrados en la institución a otros centrados en el paciente. En estos nuevos sistemas, se vuelve necesario tener alguna forma de interconectar toda la información de salud que se genera para el paciente en las distintas organizaciones, servicios y dispositivos con los que interactua a lo largo de su vida. Actualmente, estas organizaciones, servicios y dispositivos almacenan la información de sus pacientes en sus propios sistemas de información de forma aislada. La mayoría de las veces estos sistemas de información no están interconectados, lo que hace muy difícil poner en común la información de un paciente dispersa en varios sistemas. Por ello, es necesario desarrollar soluciones que permitan a los desarrolladores de sistemas de información sanitaria consultar toda la información de un usuario y ofrecerla organizada en torno a él. Esta tesis doctoral define el concepto de trayectoria personal de salud (una sucesión de registros personales de salud a lo largo del tiempo) para organizar y representar esta información. Para ello, se propone un método original utilizando técnicas basadas en distintas tecnologías actuales, como blockchain, process mining, data mining o data science. Como resultado, se consigue ofrecer un Personal Health Trajectory framework como medio para ofrecer la información del paciente organizada como una trayectoria de salud. Este framework posibilita la creación de sistemas sanitarios consumiendo esta información mediante el desarrollo de lo que denominamos aplicaciones y sistemas conscientes de la trayectoria de salud. Gracias a esta tesis, se acerca la llegada de futuros sistemas sanitarios centrados en el paciente a través de la Ingeniería del Software y las Tecnologías de la Información.

Palabras clave— Personal Health Record, eHealth, Personal Health Trajectory, Software Engineering.

Abstract

Due to the globalization of recent years, it has become increasingly common for organizations to offer services jointly with other organizations in the same scope. The healthcare field is precisely one in which there is an increasing tendency to offer this type of service. One of the reasons for this is the paradigm shift that healthcare institutions are undergoing toward patient-centered services. Thus, it is becoming increasingly common to hear about the transition from today's institution-centered healthcare systems to patient-centered ones. In these new systems, it becomes necessary to have some way of interconnecting all the health information that is generated for the patient in the various organizations, services, and devices with which she interacts throughout her life. Currently, these organizations, services, and devices store their patients' information in their own information systems in isolation. Most of the time these information systems aren't interconnected, making it very difficult to put in common the information of a patient scattered in various systems. Thus, it's necessary to develop solutions that allow health information systems developers to consult all the information of a user and to offer it organized around her. This dissertation defines the concept of the Personal Health Trajectory of the patient (a succession of Personal Health Records ordered by time) to organize and represent this information. For this purpose, an original method is proposed using techniques based on different current technologies, such as blockchain, process mining, data mining, or data science. As result, a Personal Health Trajectory framework is provided as a means of delivering patient information organized as a health trajectory. This framework enables the creation of health systems consuming this information through the development of Personal Health Trajectory-aware applications and systems. Thanks to this dissertation, the advent of future patient-centered health systems becomes achievable through Software Engineering and Information Technologies.

Keywords— Personal Health Record, eHealth, Personal Health Trajectory, Software Engineering.

Contents

List of Figures

List of Tables

Part I

Summary of the dissertation

Chapter 1

Introduction

Contents

Someone's intelligence can be measured by the quantity of uncertainties that he can bear

Immanuel Kant

This dissertation presents a set of approaches, proposals, and tools that lead the IT infrastructure of the actual institution-centered health systems towards new patient-centered ones through the definition of the Personal Health Trajectory. In this chapter, Section 1.1 starts presenting the research context of this dissertation. Then, the problem that drives this dissertation is motivated in Section 1.2. Section 1.3 presents the goal of the dissertation as well as the general and specific objectives, together with the hypothesis to be refuted or rejected on it. Section 1.4 details the research methodology followed throughout the Ph.D. The contributions and publications obtained on it are summarized in Section 1.5. Finally, Section 1.6 outlines the structure of the rest of the dissertation.

Technological advances in the healthcare domain are leading to improvements in the services provided to patients. The digitization of medical testing has greatly aided in the management and harnessing of healthcare data. In addition, the use of connected smart devices from the Internet of Things (IoT) and the Internet of Medical Things (IoMT) [14] has helped provide more continuous patient monitoring. These devices, combined with the increasingly complete data generated by healthcare institutions, enable more advanced diagnostics.

However, most of these healthcare institutions and devices work on data from a single information system. In today's globalized society, a person will probably interact with several healthcare systems throughout her life, in addition to employing several wearable health devices and interacting with smart devices from Smart Cities, which generate data outside these institutions. If each of these systems keeps its data separate, different partial representations of the patient's health reality will be generated. These multiple representations, in addition to being potentially sensitive to the presence of inconsistencies between them, have other implications, such as that a medical process may not have access to information crucial to the person's health decision-making.

Providing a way to merge the health data of an individual and provide it in a way that allows tracking of her health over time could be a solution to the above problem and a breakthrough in what is known as Precision medicine, moving the current Electronic Health Records (EHR) towards what is called Personal Health Records (PHR) [15]. EHRs are electronic records generated and managed by physicians in health systems. In contrast, PHRs are records that can be generated by physicians, patients, hospitals, pharmacies, and other sources, being managed by the patient herself.

The need to create health systems aware of the patient's health trajectory has been present in the field of medicine and nursing for years [16]. Works such as [17] and [18] begin to address this problem. However, they still do not offer a complete solution and present many limitations. For example, who is in charge of maintaining that global view and ensuring access to it. Or how to use the data from the patient's global view in the software applications that want to consume it. It is difficult to envisage that healthcare institutions would leave the management of the data they themselves generate to the patients, as proposed by PHRs. Moreover, even in the case of many works that achieve data integration, they do not include the enrichment and processing of the data in such a way as to provide added value.

This added value can be what in this dissertation we have called Personal Health Trajectory, which consists of having a complete and functional trajectory of the complete health of the patient. Not only by performing a mere integration but by means of advanced techniques that interpret and mine this data. To this end, we propose to design and implement a software development framework (Personal Health Trajectory Framework) that allows connecting different sources and types of data (from heterogeneous sources such as institutions and devices that will continue to manage the data they generate), to perform a process of filtering data from smart devices and a subsequent process of enrichment and interpretation of all integrated data.

Through this Personal Health Trajectory Framework, new healthcare application developers can access a patient's health trajectory data and create applications with more complete and higher quality data, following the data-driven medicine approach: an approach that argues that using the latest analytical techniques can lead to better health outcomes and help many more people.

1.1 Research Context

This dissertation seeks to offer a complete and functional Personal Health Trajectory with all the patient's health data through a Personal Health Trajectory Framework. To achieve this, it has been necessary to make contributions to different scientific areas through the use of software engineering and new technologies. These areas are detailed below and the reader is made aware of the state in which they were at the time of the development of this dissertation.

1.1.1 IoT and IoMT devices in healthcare processes

IoT devices are becoming more and more common. Terms such as smart homes, smart cities, or smart offices have become more common in recent times, at the same time as users' interest in this type of device is growing. According to the Plume IQ Smart Home Market Report [19], by 2022 a promedium home have 17 smart devices on average. It is estimated that there are 13 billion devices in operation at the time of writing this dissertation [20]. Moreover, predictions are that this number of devices will continue to increase, reaching 75 billion IoT devices by 2025 [21]. Considering that the world population figure at the time of writing this dissertation is around 8 million people, its means that today each person owns an average of 1,62 connected smart devices in the various environments in which they interact on a daily basis. And that this number will grow to 9 devices by 2025.

One of the main reasons for the success of this type of device and the estimated growth in its use is that they help people in their daily tasks. Tasks that are carried out in different domains [22]: from connected vehicles to healthcare, among others. It is precisely in the latter area that the use of these devices opens the door to many new possibilities in the care of people. Especially in the case of elderly care in nursing homes and similar environments [23], where these technologies can help maintain or improve care while reducing the costs of these [24]. Global IoT in the healthcare market was valued at approximately 61 billion U.S. dollars in 2019 and it was expected to reach over 260 billion U.S. dollars in 2027 [25].

There are many IoT devices that can provide relevant information for healthcare processes. From specific devices for this field, such as the so-called Internet of Medical Things (IoMT) [14, 26], to devices designed for other tasks but that collect information that can be useful to know about the user's health. For example, devices that record the user's sports tasks may not only be useful for this purpose but may also provide information relevant to the user's care, such as their sedentary habits. Even other day-to-day activities can provide information relevant to people's health, as shown by existing proposals in the field of Activity Daily Living (ADL) analysis [27].

In addition to these personal devices, other devices that are equipped in environments such as smart cities and that are not aimed at generating information on a specific person can also help in the health care of users living in that city [28]. For example, pollution meters installed to regulate traffic in large cities can provide information about the levels of pollution to which users living in a certain part of the city are exposed [29]. This information can be relevant for future diagnoses in which this information can condition the treatment or the recommendations given to the user after the treatment.

Already in the area of IoMT devices, the information that these devices can provide about the user's health is evident and as varied as medical devices begin to become smart. From hand hygiene monitoring to networked contact lenses, smart insoles to detect falls, Depression and mood monitoring devices, and ingestible sensors [30]. All of these can make contributions to healthcare processes. The biggest barrier to their adoption today, and the one that manufacturers of these devices must face, is that they must provide a level of accuracy that not many of these devices are lucky enough to achieve—even when new proposals are working on it [31]. In addition, another impediment they present, and which software engineers must face when designing the systems in which these types of devices interact, is that their integration with the healthcare information of the institutions themselves is problematic [18]. For the physician to be able to visualize and access information from all the user's IoMT devices is still difficult—and this problem can be extended to any type of IoT device mentioned above.

1.1.2 Patient-centered health systems

Today, healthcare institutions follow a purely institution-centric approach to data management. Each institution stores and manages the data it generates by itself for each patient [16]. The same happens with the IoT devices mentioned in the previous section. The manufacturers of the different brands of IoT devices provide proprietary services for their devices to store their users' data. Rarely is the integration of data from heterogeneous devices [32] or of this information with that of healthcare institutions proposed. Even when this information provides clear benefits and is beginning to be used as part of healthcare processes [33, 34].

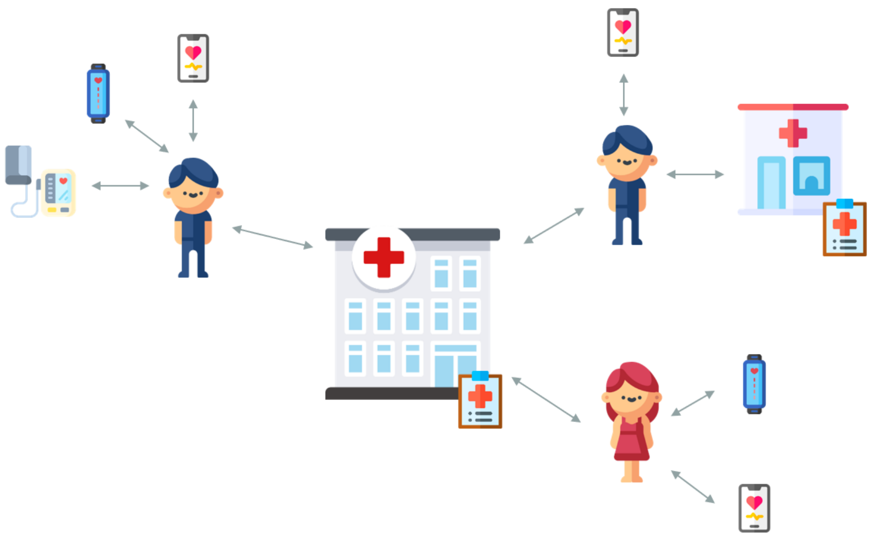


Figure 1.1: Institution-centered health systems

This situation translates into patients' health data being scattered among the different devices and institutions with which they interact throughout their lives (see Figure 1.1). This has a series of implications. From the point of view of the institutions and services, it increases the security and reliability of this data on the part of the institutions. None of them wants to cede control of the data they generate to third parties that could misuse it (especially in the case of data as sensitive as health data) [35]. From the patient's point of view, it limits the quality of the care that could be provided to her, as she does not have all her health reality when making decisions regarding her health care [16].

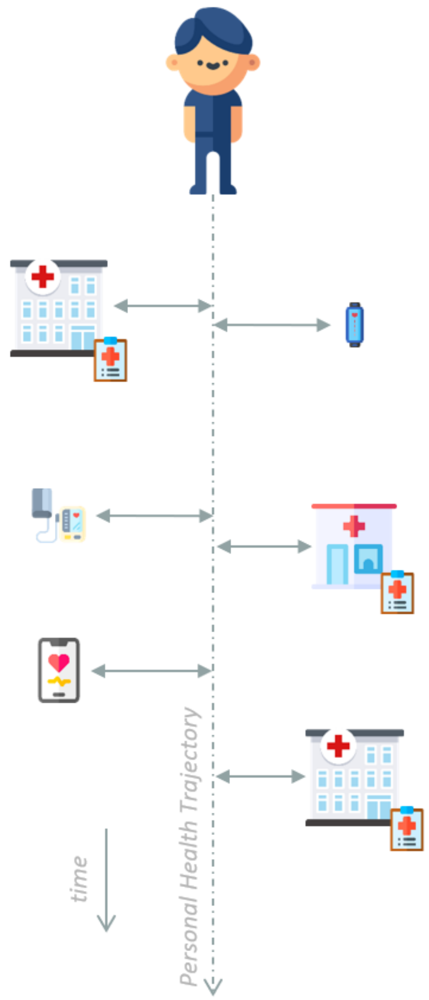


Figure 1.2: Patient-centered health systems

Taking into account that healthcare processes must be carried out for the sake of the patient, health professionals have been demanding for years the need for technological solutions to solve the aforementioned limitation imposed on them by the use of institution-centered health systems [36]. For this reason, new proposals are beginning to be defined in which the information revolves around the patient [36]. In this way, it is proposed to move from institution-centered health systems to patient-centered health systems.

In these new patient-centered health systems, patients are at the center of the information and all information is organized around the patient (see Figure 1.2) and not around institutions. The most common way in which this information is organized around the patient is by creating complete historical landscapes with all the patient's information (such as the Personal Health Trajectory proposed in this dissertation and shown in the previously named Figure 1.2). These views can have many advantages, such as providing a more accurate picture of the evolution of the patient than a fragmented view such as that offered by institution-centered health systems. It also offers the possibility of opening the door to new approaches to improve the quality of care and data security through concepts that are already being applied in other fields. For example, concepts such as the traceability of health data [9].

These proposals have arisen thanks to the advent of novel technologies such as blockchain [37], which allow the creation of software structures capable of generating patient-centered solutions that do not compromise what the institutions are looking for [35]. For example, by not implying a need to move the data from the institutions generating them to other repositories, where the data is physically integrated, as previous proposals did [38, 39]. Blockchain-based solutions manage to make the data of patients interoperable while they remain stored in the institution-centered information systems of the institutions and IoT services. Not surprisingly, this technology has opened the door to a large part of the technological proposals that seek to support future patient-centered health systems [40, 41, 42, 43], bringing the future arrival of this type of system closer. Blockchain is shown to be the most promising of all the technological alternatives up to now [35, 37], outperforming other more classical alternatives such as the use of cloud-based systems [44, 45]. In a great part, due to its distributed nature, as well as its guarantees on data security and privacy [35].

1.1.3 Automatic decisions using health data

The fact of having a large amount of health data makes it complex to be able to analyze it manually by doctors themselves. Therefore, proposals that seek to analyze this data using advanced software techniques are becoming increasingly common [46]. There are already many proposals that propose the use of Machine Learning and Deep Learning techniques that are capable of creating models capable of interpreting the data and making predictions based on a large number of variables [47, 48, 46].

In addition, the aging of the population is one of the factors that is causing this increase in the demand for care and which makes it necessary to include these techniques in order to maintain the sustainability of healthcare systems. 19% of the European population is over 65 years of age, and this figure is expected to increase due to the falling birth rate and the increase in life expectancy [49]. Numerous patients experience diseases and capacity declines that are typical of an aging population as they get older. Many of these diseases and losses progress over time and exhibit a comparable evolution in individuals with comparable characteristics [50]. Examples of these include dementia [51] and the gradual decline in the functional profile of seniors [52]. According to [50], these ability deficits frequently exhibit the same patterns of progression in patients with comparable characteristics. This enables medical experts to predict how the capacity loss will continue and to take swift action to stop it. An investigated alternative for this is to utilize automatic decision techniques to analyze the patient's progress up to this point as a time series and predict future values [46].

Similarly, in the field of preventive medicine, there are proposals that allow, based on a patient's health measurements at a specific moment, to determine if the person suffers from any illness [53][54]. However, the analysis of these data is not trivial. Especially due to challenges inherent to the characteristics of health data, such as its high dimensionality, irregularity, and sparsity [47]. Added to this is the bias of the data, as in many cases only data from patients suffering from a particular pathology or clinical condition to be analyzed is collected. In order to create models with these data, it is also necessary to have data from healthy patients or to make use of techniques that allow the data to be pre-processed prior to their use in predictive models. Some proposals are already aware of this problem and are starting to propose solutions from the data collection phase [55].

In addition, linked to the above, being able to collect the amount of data needed for these models means that healthcare professionals need to perform a large number of assessments [56]. For the sake of have an historical view of the patient, this requires also a constant reassessment of patients. Many of these assessments involve collecting large amounts of information regarding different variables associated with the patient's health status [57].

Collecting data from several variables in each assessment is time-consuming which infringes on their limited time and reduces their patient-facing care time [58]. In order to care for their patients, health professionals are compelled to undertake fewer assessments, which lowers the sustainability and quality of care.

The initial set of inputs may be reduced just with minor accuracy loss if a clinical assessment contains duplicated or irrelevant variables. The World Health Organization Disability Assessment Schedule II (WHODAS-II), a tool for evaluating functioning, serves as an illustration of this. Despite the fact that the original version had 36 items, certain researches have supported the usage of a 12-item version [59, 60]. However, it is not simple to determine which variables have redundant information and can be removed. To determine which reduced collection of variables contains the same information as the original set, statistical techniques are beginning to be applied [61].

Feature Selection and Machine Learning/Deep Learning techniques are closely related and are being employed together in the analysis of health data [61, 48]. Feature Selection techniques are employed to pre-process the input variables in any of the main types of Machine Learning and Deep Learning problems [46]: classification, regression, and clustering. Feature Selection is frequently used in classification problems [61, 62, 63] and clustering [64]. However, they are not commonly applied to regression problems[65, 66] and their potential could be investigated further [67]. Many healthcare problems are regression ones.

Applying these techniques to healthcare data can uncover new knowledge about the data and improve patient care processes [11]. However, these techniques are computationally expensive and their applicability can be complicated if they try to be used on complex data such as health data [47]. To try to solve this, other computational models that can be applied to analyze health data have begun to be studied. In this sense, quantum computing opens the door to analyze these data [68, 69, 70], adapting, among others, the current Artificial Intelligence techniques to the quantum computing paradigm [71].

One example of health data that is unmanageable for current computers and that quantum computing could solve is the study of pharmacogenetics. Pharmacogenetics allows the study of the effects of an individual's genetic variability on his or her response to certain drugs. In other words, this discipline makes it possible to prescribe drugs taking into account the possible effects that these may have on a patient with specific genetic factors. However, providing a safe and effective pharmacological therapy using traditional software systems is a complex task, from a computational point of view and from the point of view of high processing time requirements [72].

If the use of these computational techniques could be integrated as part of the classic systems in which patient health data are stored, it would allow the analysis of this type of data that currently cannot be analyzed. These data become part of the Personal Health Trajectory Framework presented in this dissertation and their analysis in conjunction with the rest of the Personal Health Trajectory would improve the quality of patient care.

1.2 Problem Statement

The technological advances that have taken place in healthcare in recent years have made it possible to improve the services provided to patients. Part of these benefits stems from the fact that healthcare information systems have been digitized. In addition, apart from information from the healthcare institutions themselves, the use of Internet of Things (IoT) and Internet of Medical Things (IoMT) devices [14, 26] is becoming increasingly common, generating new data on patients' health. This data can be used alongside traditional medical data to provide more advanced solutions.

Therefore, more and more institutions and services are generating electronic health data for the patient. Not surprisingly, it is becoming less common to talk about patient Electronic Health Records (EHRs) [73] and more common to talk about Personal Health Records (PHRs) [36]. While EHRs only encompass computerized records created and managed by physicians in healthcare systems, PHRs encompass all the health records of a patient. These can be generated by physicians, but also by patients themselves, their devices, hospitals, pharmacies, and other sources. Moreover, unlike EHRs, PHRs are managed by the patient.

However, although more and more services are generating data for the same patient, most health systems today still keep their patient data stored in isolation in their own information system. When a new patient arrives at a health system, she is registered for the first time in the information system, where the data produced by the successive interactions that this patient has throughout her life with that health system will be added. These data are not conditioned by the data stored by other health systems about their interactions with the same patient. They are not even aware of them. Thus, what is being obtained in each health system is a partial and isolated representation of the health reality of each patient.

These partial representations of the patient mean a problem when it comes to offering the best treatment for her since the diagnoses are never based on the complete reality of the patient's health. Decisions are never made by being aware of all the patient's information. As well, these different representations are potentially sensitive to the presence of inconsistencies between them. This problem is increasing as the number of services generating a patient's health data grows. If each of their systems maintains their patients' data separately, crucial information about a patient's health may not be available when needed [74]. Thus, although the data maintained by each institution is already useful to patients, it acquires added value when brought together.

An example is proposed to explain the issues involved. *Paula is a Spanish girl suffering from diabetes. On one of her trips to China, Paula faints due to hypoglycemia. She is treated at a health center in China, where she undergoes several blood glucose measurements. However, when Paula returns to Spain, she cannot give the data of these measurements to her regular doctor,* *as they have been registered in the Chinese health system. The same thing happens with a smart device she has at home. This device measures her health, such as her blood glucose. Until Paula goes for her regular check-up, she cannot give the data of these measurements to her doctor. If Paula should suffer another fainting spell before this, the attending physician cannot access Paula's latest glucose measurements.*

Providing a way to integrate a patient's health data and provide it in a format that allows tracking of her health over time may be a solution to the above problem. This integration can be done physically, by integrating all health data into the same storage system, or by providing a single point of access for distributed data that makes it interoperable. In either case, a single, global view of the patient's entire healthcare reality is obtained.

The creation of healthcare systems that take into account the integrated and global vision of the patient's health, as proposed in this doctoral thesis through the concept of Personal Health Trajectory, is something that has been demanded from the fields of medicine and nursing for years [16]. There are multiple researchers around the world who have been working on it for years [38, 39, 75, 44, 40, 41, 76]. However, as far as the authors know, there is no one who has proposed a solution that can be fully adopted by healthcare systems and services for IoT/IoMT devices. Either because they propose very intrusive solutions for institutions and services, or because they offer solutions that are halfway, offering a global vision that is not easy to access by healthcare professionals in institutions, when treating the patient. In addition, for the proposal to be fully functional, it must not only integrate its data but must also be able to facilitate its interpretation [47, 77] and make it useful for use in automatic tools that assist healthcare professionals in their diagnoses. These tools are increasingly common in healthcare [48, 46] and the health data that are part of the patient's Personal Health Trajectory should be ready for application in these.

The interest in this type of proposal does not arise only in isolated works but is part of several complete research projects. Specifically, in projects in the field of software engineering applied to health and gerontechnology, in which the author of this doctoral thesis and his directors are or have been involved, some researchers are working on the definition of the Individual Care Plan (ICP) [78, 79, 80]. This ICP proposes a method of care centered on the elderly, similar to previous patient-centered proposals. It is within the 4IE and 4IE+ [81] projects, where the improvement of the lives of the elderly through technology is studied. In these projects, there is a complete line of comprehensive care for the elderly. Not only with the ICP but also with the Multidimensional Integrated Assessment Platform for Elderly (MIAPe) [82, 83], a platform that allows the integrated assessment and monitoring of the health of elderly patients in different Portuguese healthcare institutions, through a single software platform.

It is clear, therefore, that the problem addressed in this doctoral thesis is relevant to society as a whole. It affects a large part of the population. Therefore, it is necessary that researchers in the area of information technologies applied to healthcare dedicate their efforts to create systems that are aware of the problem and solve it, as current proposals for patient-centered healthcare systems attempt to do. However, current efforts are not sufficient. Therefore, this doctoral thesis tries to make a contribution to the solution of the problem, offering a new way to develop completely patient-centered healthcare systems, through the concept of Personal Health Trajectory—see Appendix C [1]. This proposal makes it possible to generate a global and unique vision of the patient, with all her data integrated and enriched, to generate extra value with respect to the raw data, the result of the new information inferred by connecting previously dispersed and unconnected data. This is expected to improve the healthcare received by people like Paula, since diagnoses will be made on the basis of more complete and higher quality data, following the data-driven medicine approach.

1.3 Dissertation Goal: Hypothesis and Objectives

This dissertation has addressed a number of issues that are defined below, its main objective being to develop a framework (and its associated development methodology) that provides the health trajectory of users from a single point of access. In order to achieve this, other more immediate objectives must be met, such as the incorporation of health information from IoT and IoMT devices, the integration of data from different sources, and the mining, analysis, and enrichment of this data. Some of these objectives have already been partially addressed by existing proposals in the literature, which have been taken as a basis to start the pursuit of the corresponding objective(s) of this dissertation in each case. In the area of data integration, works such as [35] by Kassab et al. analyze the use of Blockchain technology to integrate user EHRs between different healthcare systems; [15] by Roehrs et al. implements a PHR model that integrates distributed EHRs using blockchain and the openEHR interoperability standard. Within the same group where the thesis is going to be developed, there are proposals to integrate data from IoT/IoMT devices. Flores et al. propose a [84] solution based on the semantic web.

At the beginning of the dissertation, a series of **hypotheses** have been established to corroborate or reject its achievement, whose result is commented on in Chapter 8 of this document. These hypotheses are:

- **H1.** The incorporation of the concept of Personal Health Trajectory in the field of eHealth is going to allow for building better health systems.
- **H2.** The integration of data from IoT/IoMT devices along with EHRs in healthcare systems is going to enable a more accurate understanding of a person's health over time.
- **H3.** The enrichment and improvement of the interpretability of integrated data from different sources will make it possible to find relationships between data that were not previously contemplated.

In order to achieve the contributions set for this dissertation and to verify the previous hypotheses, a series of **objectives** have been set to be completed. These objectives have been classified into General Objectives (GO) and Specific Objectives (SO), in order to facilitate their achievement:

- **General Objectives (GO)**
  - **GO1.** Provide a framework, with an associated development methodology, for accessing the health trajectory data of an individual.
  - **GO2.** Unify health information systems to achieve PHT for patients.
  - **GO3.** Integrate data flow from IoMT/IoT devices with healthcare information systems.
  - **GO4.** Enrich and interpret patient data after integrating it from different sources.
- **Specific Objectives (SO)**
  - **SO1.** Implement an interface or API to provide access to the data in our framework.
  - **SO2.** Apply data mining algorithms to enrich the knowledge provided by a patient's health trajectory data.
  - **SO3.** Apply feature selection algorithms to determine which data are most relevant to a diagnosis from the entire integrated data.
  - **SO4.** Standardize proprietary information system technology data, through the use of interfaces, such as REST.

- **SO5.** Use blockchain, and specifically the concept of blockchain federation, to achieve integration of a user's health data.
- **SO6.** Apply process mining algorithms to filter information from the constant data stream of IoT/IoMT devices.

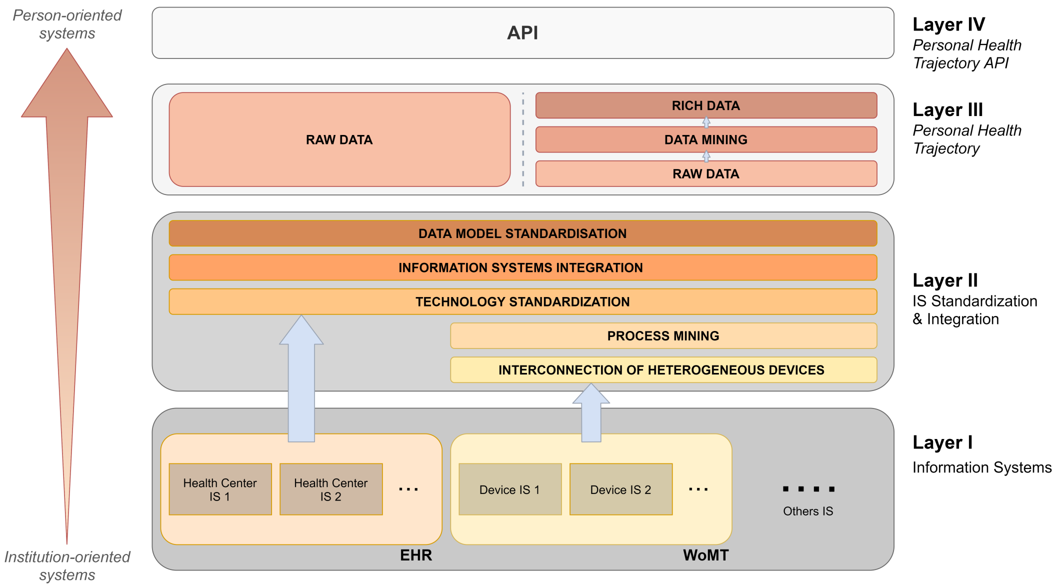


Figure 1.3: Architecture proposed for the Personal Health Trajectory Framework [1]

From the definition of the previous objectives, we extract the need to have an architecture (Figure 1.3) that meets them and supports the proposed Personal Health Trajectory Framework. It was reviewed and contrasted with a panel of experts at a Ph.D. Symposium at the beginning of the dissertation. The defined objectives are thus distributed among the different layers of its architecture:

- **Layer I: Information Systems.** Maintainer of patient data. It is composed of the current information systems and does not contribute to achieving any of the defined objectives.
- **Layer II: IS Standardization & Integration.** Responsible, firstly, for standardizing the information stored in the previous layer regardless of the technology employed to store it; and secondly, for unifying the data of each information system. In the case of IoT and IoMT devices, it will also be responsible for the processing of the stored data streams.

It has attributed the general objectives GO2 and GO3, and the specific objectives SO4, SO5, and SO6.

- **Layer III: *Personal Health Trajectory.*** Responsible for providing health trajectory data for a person. This data may be provided "raw" (unprocessed) or with greater expressiveness, after applying Data Mining techniques on them. It has attributed the general objective GO4 and the specific objectives SO2 and SO3.

- **Layer IV: *Personal Health Trajectory API.*** Responsible for providing a point of access to a person's health trajectory data to all those who want to develop software on *Personal Health Trajectory.* It has attributed the general objective GO1 and the specific objective SO1.

Therefore, based on the problem statement of Section 1.2, the hypotheses established, the objectives marked and the existence of some studies in the literature that partially solve the problem, the **research areas where this dissertation should focus** are limited to the following:

- **Distributed Data Integration**. In recent years, the use of Blockchain to store EHRs is expanding [35] and has been demonstrated as one of the most suitable technologies for that. So, our solution should allow the integration of data must be based on blockchain but allow the integration from different blockchains and the interaction between them, creating a "federation of blockchains". This contributes to reducing the intrusiveness of this kind of proposal.

- **IoMT/IoT device data flows**. Devices provide a continuous stream of data that can sometimes be interesting, but in other cases provide too much information. Process mining techniques will be used to filter and interpret this information collected from user devices.

- **Enriching and improving data interpretability**. Patient data, once integrated, can provide information that they did not previously provide separately. Machine learning algorithms will be used to perform data mining processes that give greater expressiveness to integrated "raw" data from different sources. In addition, procedures and solutions to help the healthcare professional and algorithms interpret and determine which patient health information is most relevant to each diagnosis must be defined.

- **Personal health trajectory**. Guiding the approach to medical data to track a person's health throughout their lifetime and deliver this data through a framework.

1.4 Research Methodology

In order to ensure that the various objectives and sub-objectives established in the development of this dissertation are achieved, the different activities with which they are achieved must be correctly planned. The best way to do this is to use a formal methodology. In this case, Design Science [85, 86] is chosen.

Design Science is a methodology oriented towards research projects. Normally, it is applied to projects in the field of Information Technology. Specifically, to Engineering and Computer Science disciplines, although it can be used in many other disciplines and fields. Design Science tries to give a more pragmatic nature to the research objectives. In this methodology, the creation of innovation goes through the creation of artifacts. According to Design Science, researchers see an artifact as something that should support people in a practical way. When Design Science is applied to information technology research, artifacts are any model, method, social innovation, development method, software, or hardware, among others. Therefore, for Design Science, researchers are not disinterested observers, but take on the role of designers who create useful objects. To achieve this, Design Science offers Information Technology researchers some guidelines for the evaluation and iteration of research projects [85].

There are multiple publications on Design Science. Specifically, the one [86] by Hevner et al. is centered on apply Design Science to Information Systems research—the discipline of this dissertation—and defines seven specific guidelines for this:

1. **Design as an artifact:** A Design Science research must generate an artifact.

2. **Problem relevance:** The objective of Design Science research must be to solve a relevant problem for society.

3. **Design evaluation:** The utility, quality, and efficacy of the developed artifact must be meticulously evaluated.

4. **Research contributions:** An effective Design Science research must have associated a clear and verifiable contribution to the domain to which the attached artifact belongs.

5. **Research rigor:** Both the construction and the evaluation of the artifact must be done following rigorous methods

6. **Design as a search process:** In order to obtain an effective artifact, it is necessary to make use of all available means, as long as the laws of the environment are complied with.

7. **Communication of research:** The Design Science research must be presented effectively, not only for the technical audience but also for management-oriented audiences.

In [86], the authors presented Design Science as a research paradigm. They do not present a detailed process for performing design science research. Due to this, the three-cycle view—Figure 1.4—was presented later in [2] by Hevner. This view, define Design Science as an iterative process. Therefore, the execution of Design Science is not done in a single sequential execution, but three cycles are defined and executed iteratively. These cycles are not isolated, but there is a certain interaction between them. Specifically, the three cycles are:

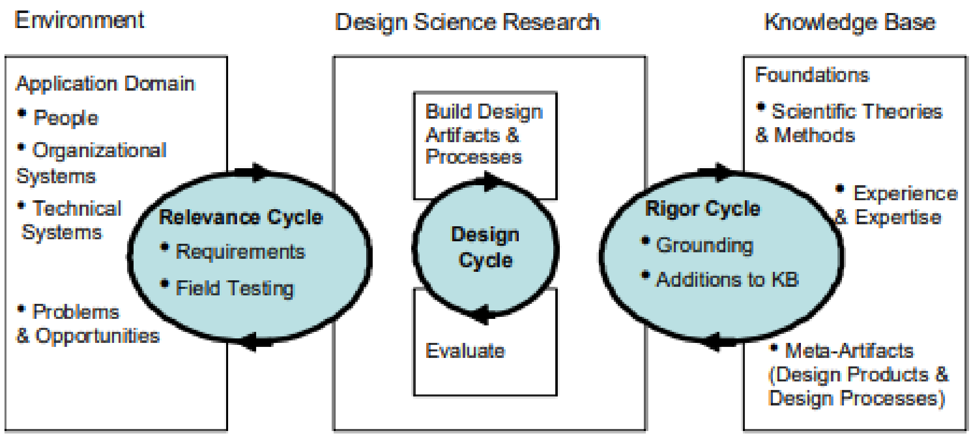


Figure 1.4: Design Science Research Cycles [2]

1. **Relevance Cycle:** It is the first cycle. The one that starts the research. To do this, it analyzes the environment, looking for the problems that exist in it. In this cycle, the requirements that the artifacts must meet are defined. Also, it defines how the research will be evaluated. In other words, the criteria to determine if the results obtained by the research are accepted or not are established. Thanks to this, it is possible to know if more iterations are necessary or not.

2. **Design Cycle:** In this cycle, artifacts and processes are built, using as input for this the requirements that are defined in the *Relevance Cycle.*

After building them, they are evaluated, following the criteria defined in the text Relevance Cycle again.

3. **Rigor Cycle:** This is the cycle that evaluates whether the project really makes a contribution to the scientific community and to society in general. To this end, the research carried out must contribute to the knowledge that existed before its completion in the field in which it is located.

1.5 Contributions

This section summarizes the main contributions of this dissertation to the literature. These contributions are not only limited to publications in conferences and journals but also new research collaborations between research entities through research stays and publication in public repositories of new development tools available for their use by other researchers or even in the industry. The latter can help to transfer the results of the dissertation from academia to industry.

1.5.1 Summary of Contributions

In pursuing the goal of this dissertation, we have made several contributions classified into three main research topics. In this subsection, for each of these research topics, some research context, the problems addressed, the solutions proposed and the publications obtained are discussed.

Inclusion of IoT and IoMT devices

Context: If the ultimate goal of this dissertation is to be able to offer a complete Personal Health Trajectory Framework, offering access to all the data on a patient's health in order to improve patient follow-up over time and, thus, patient care, IoT and IoMT devices can offer a continuity of patient health that healthcare institutions themselves could never achieve [31]. Therefore, it becomes necessary to find a way for the information from these devices to be integrated in a consistent manner with that of the healthcare institutions in our proposal. However, the biggest problem with this is that in many cases the use of these devices is subject to manual actions that users must perform with them. This implies that the user establishes a routine in their use so that measurements are performed consistently and relevant information can be extracted for the Personal Health Trajectory. In the case of aging people, who are also the ones who need more health care and who demand a greater monitoring of their health [24], the fact that these users can easily interact with this kind of devices and even establish a routine in their use is not very credible [5]. Moreover, smart devices that can generate relevant information about people's health (whether they are personal smart devices or even devices equipped in Smart Cities and that measure different parameters that affect people's health) in many cases generate a data flow (by data I mean measurements, actions or similar) that is not very useful by itself. This flow would provide really relevant information for the Personal Health Trajectory if it were mined as a process from which it could be extracted if certain patterns are really present in that data flow.

1. *Problem statement:* It is necessary to reach the Automatization of interactions with IoT/IoMT devices to get data from these devices generating the least impact on users.

   Contribution: To solve this problem, proposals have been made to automate IoT devices of any kind (not only IoMT) by learning from the user's behavior with their devices in their different environments and in the different contexts in which they interact. This learning is done through Machine Learning techniques that are executed in the user's own smartphone, generating a model capable of reproducing its behavior through supervised learning. With this, it is considered that, once the model has learned enough about the behavior with a given device in a specific environment and context, it automates the actions with this device. If the user changes behavior, correcting the automatized actions, the model learns from this change in behavior and readjusts the use made of the device. In this way, the amount of manual interactions that a user must perform with her devices is greatly reduced to only those necessary for the model to learn the behavioral pattern that guides the user's usage of the device. If such a pattern did not exist, the interactions would never be automated. All the details of this proposal were published in *PerCrowd'19* [4]. In addition, the proposal was subsequently adapted for use in nursing homes, which involve several aging people interacting with the various devices in the nursing home and which, in many cases, are located in rural environments with difficult access to a network connection. This allows the creation of Smart Nursing Homes that enable this information to also be collected for elderly users of these institutions. The results of this proposal were published in *WCMC* [5] and in *JCIS'21Smart* [87]. At the same time, we also worked on collecting information on other actions related to the health of the patients, such as taking medication. For this purpose, a virtual assistant was developed to monitor the taking of these medications. Its development is documented in the publication *IWoG'19* [3].

2. *Problem statement:* Extraction of the most relevant information from the dataflow of IoT/IoMT devices is necessary in order to not integrate all patient-related measurements, actions, and events into the Personal Health Trajectory.

   Contribution: This dissertation proposes the use of process mining techniques to extract the most relevant data from the data flow generated by any type of IoT device. In this way, we have proposed an architecture that we call Federated Process Mining capable of mining groups of users with common behaviors that present a pattern of interest in their behavior. The user's behavior is defined by the information collected in their smartphones from their smart devices or from the use they make of their applications. In this way, for example, it is possible to know which users comply with a pattern that represents a common behavior in people who subsequently develop a pathology or that is a risk factor in an ongoing pathology, and to search for adjacent patterns that users of this group also present and that, therefore, may be related. For example, it can allow health professionals the detection of sedentary lifestyles in people with cardiovascular problems. The presence or non-presence of these patterns is what will be documented in the Personal Health Trajectory rather than (or together with) the continuous data stream that an IoT device can generate. The results of this proposal were published internationally and nationally in *IS* [6] and *JCIS'22SOWCompact* [88], respectively. In addition, two publications about a tool developed based on this proposal and called Social Events Analyzer (SEA) were carried out in *JCIS'21SEA* [89] and *ICWE'22* [7].

Interoperability of the healthcare systems

Context: Currently, the information systems of the healthcare institutions and intelligent devices mentioned above store data in an isolated way and independently of the rest of the healthcare systems. In the best of cases, small cooperations are established between different systems to carry out collaborations that pool data from all of them [90]. However, considering these collaborations on a large scale is hard to believe, since there are no software solutions capable of doing this in a non-intrusive way. The most widely accepted solution, both in healthcare and in other areas, is the use of blockchains to integrate or interoperate (depending on whether the blockchain stores the data or only serves as a structure that stores references and allows them to be located) the data of the different institutions that subscribe to a consortium. This implies that all systems adopt a common blockchain, so it is still difficult to believe that on a large scale this can be feasible. In the case of this dissertation, achieving this integration or large-scale data interoperability is necessary, in order to have access in the Personal Health Trajectory jointly to all of a patient's health data [1]. Regardless of how many healthcare institutions you visit or how many smart devices you interact with. Furthermore, formatting this data as a health trajectory improves the care capacity of healthcare providers [16] and enables new concepts such as health traceability [9].

1. *Problem statement:* Create a mechanism for integration of distributed health data as a Personal Health Trajectory that is non-intrusive and applicable on a large scale.

   Contribution: A blockchain-based software architecture has been defined that extends the concept of using one blockchain per patient that has been used in current proposals to interoperate distributed patient data. This architecture is called blockchains' federation and is based on the use of blockchains in two layers: a lower layer with patient blockchains, where each patient has a single blockchain that stores reference to where their data is stored in the different institutions; and an upper layer consisting of a single blockchain that is responsible for federating the other blockchains and stores reference to where each patient's blockchain is deployed. The only thing that all the institutions must share in order to access the blockchain containing the Personal Health Trajectory of each patient is this upper blockchain, which we call the main blockchain. Unlike sharing a blockchain with all the data from all the institutions, here they are only sharing a blockchain with references that act as a directory. The data from the smart devices can be integrated by the manufacturer as if it were another institution or through the patient's smartphone, where the patient has access to her blockchain and can remotely write to it, without the need to have a local node on the smartphone, through blockchain technologies that allow this. To facilitate the referencing of information from patients' blockchains, the proposal offers a series of REST APIs that companies can adopt to make their data referenceable. They are also allowed to use their own mechanisms. This also makes the integration independent of the storage technology used by the institution. On blockchains' federation, a connector has also been defined that allows offering their data through an API, solving also another part of the objectives of the thesis. All this is published in an international workshop in SEH'21 [8] and in a relevant international conference in

ICC'22 [91].

2. *Problem statement:* Generation of the traceability of health data in the Personal Health Trajectory Framework

   Contribution: Taking advantage of the integration of data in a Personal Health Trajectory, a mechanism has been defined to extend this proposal and allow it to also offer health traceability as part of the Personal Health Trajectory Framework. This health traceability is similar to that already proposed for other areas such as food traceability, where it is possible to control all the states through which food goes from the moment it starts to be processed until it reaches the consumer. In this case, it allows knowing all the people who interact with a medical test by performing a read, modify or delete operation from the moment it is created, as well as controlling the changes in the content (if any). All the details about this health traceability can be found at IWoG'21 [9].

Enrichment and interpretability of the health data

Context: One of the particularities of health data is that they are very interesting for their automatic analysis with technologies such as Machine Learning or Deep Learning. The use of these techniques on this data allows for obtaining new knowledge about the patient's condition that otherwise could not be obtained. For this reason, this type of proposal is becoming more and more frequent [46]. The fact that in this case all the health data of a patient are organized as a history opens the door to new types of analysis of this data [46, 10]. For example, the study of the patient's evolution is something that needs to know all the patient's past information, becoming complicated if all the patient's past data is not considered [10]. However, linked to this, having all the patient's data integrated can become a double-edged weapon, since it also becomes necessary to know what information to take into account at each moment [47], so as not to introduce noise both in the manual and automatic analysis of the patient's data. Considering also that, in order to predict certain pathologies, the number of variables to be measured can be many, even after applying techniques for their selection, it becomes important to look for alternative computations capable of analyzing situations where the amount of data to be handled is very large. In this sense, quantum computation has been presented as a great candidate, if it can be integrated with classical computation.

1. *Problem statement:* Be able to select the most relevant information from the Personal Health Trajectory for each diagnosis or clinical condition.

Contribution: One of the biggest problems in extracting knowledge from integrated data is that a large amount of very diverse information is being integrated. This complicates the creation of artificial intelligence models capable of predicting things and even the manual analysis of the data by health professionals in search of determinants for a given clinical condition. It is necessary to be able to select, from all the integrated data, which are of interest at any given moment. To this end, we have worked on proposals for Feature Selection, which allow us to filter which variables are really important when predicting the existence of pathology. The evaluation of the decrease in the functional profile of the elderly with age has been used as a case study. The results obtained have been published in a high-impact journal in *TETC* [11]. As well, one publication has been done about this proposal in the International Gerontechnology Conference in *ISG'22* [92]. In the same way, in the last moments of this dissertation, work has started on the development of a platform that allows health professionals to select the characteristics in an assisted, and not automatic, way. In this way, the Feature Selection techniques will only serve as a support to the health professional, and she is going to be able to contribute with her knowledge about how complex it is to collect information on certain health parameters, in relation to what it contributes to the diagnosis of the pathology that is to be treated with this information. Or the need to maintain a characteristic in order to establish links between different pathologies. At the time of writing this dissertation, the results of this part are not yet published.

2. *Problem statement:* Usage of Personal Health Trajectory as an aggregated value for the prediction of future conditions of the patient.

   Contribution: In the field of extracting new information from integrated data, the potential use of the longitudinal view over time of the patient's Personal Health Trajectory has been studied to start working on proposals that use this data to predict the patient's evolution. Having a complete view of the patient's history provides better tracking of the patient's health over time that can be used in time series forecasting techniques to predict how the patient will continue to progress based on this history and the knowledge acquired from patients in a more advanced stage who in earlier stages showed a similar evolution (as well as having similar characteristics). This evolution may determine a more or less near future, depending on the amount of data available. In particular, a first proposal has been made to validate this contribution by using again data on the evolution of the functional profile of the elderly. The results can be found published in an international workshop in *IWoG'20* [10].

3. *Problem statement:* Offer new ways of computation for a most efficient analysis of health data.

   Contribution: Another of the most novel lines that have been introduced in this research topic is the use of Quantum Computing to perform the data mining phase, given its high computational performance. In JCIS'22Qsalud [93] the authors reflected the advantages that the use of these techniques can bring in the analysis of health data. In this case, in the analysis of drug data and how their side effects affect patients. To achieve this, a way to communicate the proposed system, developed under the framework of classical computing, with quantum systems that are able to use the data provided by classical systems, perform data mining on them and return answers much faster than how classical systems would do it, has been proposed. In this sense, work has been done on proposals to use quantum systems as services that coexist in hybrid-quantum environments with quantum computing. The results of these studies have been published in different venues: from international workshops such as the one of QSET'21 [94] publication, national conferences such in *JCIS'22Quantum* [95] and *JCIS'22OpenAPI* [96], international conferences such in *QUATIC'21*, book chapters as *QSE* in Quantum Software Engineering [97], to relevant journals such as *SQJ* [98] and very relevant journals such as *IC* [13].

1.5.2 Publications

This subsection of the dissertation presents the complete list of publications that have been listed in the previous section as part of each of the three topics into which the contributions of this dissertation have been divided. On this occasion, they are organized in chronological order and divided by publication year. A brief summary of the research results obtained in each of those years is included also. The publications are listed with the same code or acronym assigned to them in the previous section. For each publication, the authors, title of the publication, venue where it was published, date of publication, and quality metrics of the venue (if available) are listed.

2020

In 2020 was the year in which the dissertation was started. However, the dissertation started at the end of October of that year, so no major contributions could be made. Only a few publications were made prior to the start of the dissertation that served as a basis for defining some of the objectives that should be contemplated in the achievement of a complete and functional Personal Health Trajectory Framework. In this case, these were publications on the inclusion of IoT and IoMT devices. Specifically, a publication was made (IWoG'19) in the International Workshop on Gerontechnology on a voice assistant that allows digital control of medication intake in aging people. A first publication (PerCrowd'20)was also made at the PerCrowd international workshop of the PerCom conference (2021 GGS Class 1 Core A+) on the automation of interactions with intelligent devices. This publication served as a basis for further publications in this line in the following year. In addition, a publication (ICWE'20) was made at the Ph.D. Symposium of the International Conference on Web Engineering (2021 GGS Class 3 Core B-) to present the dissertation idea prior to its start to test its feasibility with a panel of experts.

- **IWoG'19** [3]. Manuel Jesús-Azabal, Javier Rojo, Enrique Moguel, Daniel Flores-Martin, Javier Berrocal, José García-Alonso, Juan M Murillo. Voice Assistant to Remind Pharmacologic Treatment in Elders. *Second International Workshop on Gerontechnology*, pages 123-133, 2020.
- **PerCrowd'20** [4]. Javier Rojo, Daniel Flores-Martin, Jose Garcia-Alonso, Juan M Murillo, Javier Berrocal. Automating the Interactions among IoT Devices using Neural Networks. *3rd International Workshop on Context-awareness for Multi-device Pervasive and Mobile Computing (PerCrowd)*, pages 1-6, 2020.
- **ICWE'20** [1]. Javier Rojo, Juan Hernandez, Juan M Murillo. A Personal Health Trajectory API: Addressing Problems in Health Institution-Oriented Systems. *International Conference on Web Engineering*, pages 519-524, 2020.
  - GGS class (rating): 3 (B-).

2021

During this year we started to open the rest of the lines corresponding to the research topics of Section 1.5.1. An article (WCMC) was published to conclude the part of the automation of interactions with IoT/IoMT devices in a high-impact journal. Specifically in Wireless Communitations and Mobile Computing (JCR Q3). As well as a publication (JCIS'21Smart) on this same topic at the national conference Jornadas de la Ciencia e Ingeniería de

Servicios. We also started working on the extraction of the most relevant data from the dataflow of smart devices with a publication (JCIS'21SEA) in the same national conference. In the line of distributed data integration, the first proposal (SEH'21) was published in the international workshop Software Engineering for Health collocated with the International Conference on Software Engineering (2021 GGS Class 1 Core A++). In the area of health data enrichment and interpretability, a paper (IWoG'20) on the use of health trajectory data to predict patient evolution was published in the International Workshop on Gerontechnology. Work was also done on the analysis of new forms of computation for mining this data, through quantum computing. In this line, several publications were produced: a publication (QSET'21) in the international workshop of Quantum Software Engineering and Technology, a publication (QUATIC'21) in the International Conference on the Quality of Information and Communications Technology, and a publication (IC) in the high-impact journal Internet Computing (JCR Q2).

- **IWoG'20** [10]. Javier Rojo, Enrique Moguel, Cesar Fonseca, Manuel Lopes, Jose Garcia-Alonso, Juan Hernandez. Time Series Forecasting to Predict the Evolution of the Functional Profile of the Elderly Persons. *Third International Workshop on Gerontechnology*, pages 11-22, 2021.
- **WCMC** [5]. Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan M Murillo. Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas. *Wireless Communications and Mobile Computing.* 2021.
  - JCR IF: 2.146.
  - Rank: Q3 120/164.
- **SEH'21** [8]. Javier Rojo, Juan Hernández, Juan M Murillo, Jose Garcia-Alonso. Blockchains' federation for integrating distributed health data using a patient-centered approach. *2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH)*, pages 52-59, 2021.
- **QSET'21** [94]. Javier Rojo, Enrique Moguel, David Valencia, Javier Berrocal, Jose García-Alonso and Juan M. Murillo. Trials and Tribulations of Developing Hybrid Quantum-Classical Microservices Systems. *2nd Quantum Software Engineering and Technology Workshop*, pages 1-16, vol. 3008, 2021.
- **QUATIC'21** [12]. David Valencia, Jose Garcia-Alonso, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo. Hybrid Classical-Quantum Software Services Systems: Exploration of the Rough Edges.

International Conference on the Quality of Information and Communications Technology (QUATIC), pages 225-238, 2021.

- **JCIS'21SEA** [89]. Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal. Social Events Analyzer (SEA): Un toolkit para minar Social Workflows mediante Federated Process Mining. *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2021.
- **JCIS'21Smart** [87]. Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan M Murillo. Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas (Summary). *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2021.
- **IC** [13]. Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo. Quantum software as a service through a quantum API gateway. *IEEE Internet Computing*, pages 34-41, vol. 26, 2021.
  - JCR IF: 2.680.
  - Rank: Q2 43/110.

2022

In this last year of the dissertation, efforts have been made to close all the lines of the different research topics. In the part of the inclusion of IoT/IoMT devices, the line of extraction of the most relevant information was closed with a publication (IS) in the high-impact journal Information Sciences (JCR Q1) and the dissemination of results in other conferences such as the International Conference on Web Engineering (2021 GGS Class 3 Core B-) and the national conference Jornadas de la Ciencia e Ingenieria de Servicios. A demo tool (ICWE'22) and a summary (JCIS'22SOWCompact) of the Information Sciences paper were published, respectively. The final version of the data integration solution was also published (ICC'22) at the International Conference on Communications (2021 GGS Class 2 Core A) and the concept of health traceability was defined at the International Workshop on Gerontechnology (IWoG'21). In data enrichment and interpretability, a paper (TETC) on improving data interpretability was published in the high-impact journal IEEE Transactions on Emerging Topics in Computing (JCR Q1) and another one (ISG'22) on the International Conference on Gerontechnology. Further contributions were also made in the area of quantum computing with a publication (SQJ) in the high-impact journal Software Quality Journal (JCR Q3) and several papers (JCIS'22Quantum, JCIS'22QHealth, JCIS'22OpenAPI) in the national conference Jornadas de la Ciencia e Ingeniería de Servicios. A book chapter has been published also in the Quantum Software Engineering book (QSE). Apart from these publications, several contributions were submitted and are under review in several relevant conferences and high-impact journals at the time of writing.

- **IWoG'21** [9]. Javier Rojo, Juan Hernández, Sumi Helal, Juan M Murillo, José García-Alonso. Blockchain-Supported Health Registry: The Claim for a Personal Health Trajectory Traceability and How It Can Be Achieved. *Fourth International Workshop on Gerontechnology*, pages 22-33, 2022.
- **ICWE'22** [7]. Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal. Social Events Analyzer (SEA): A Toolkit for Mining Social Workflows by Means of Federated Process Mining. *International Conference on Web Engineering*,pages 477-480, 2022.
  - GGS class (rating): 3 (B-).
- **SQJ** [98]. Enrique Moguel, Javier Rojo, David Valencia, Javier Berrocal, Jose Garcia-Alonso, Juan M Murillo. Quantum service-oriented computing: current landscape and challenges. *Software Quality Journal*, pages 1-20, 2022.
  - JCR IF: 1.813.
  - Rank: Q3 69/110.
- **IS** [6]. Javier Rojo, Jose Garcia-Alonso, Javier Berrocal, Juan Hernández, Juan Manuel Murillo, Carlos Canal. SOWCompact: A federated process mining method for social workflows. *Information Sciences*, pages 18-37, vol. 595, 2022.
  - JCR IF: 8.233.
  - Rank: Q1 16/164.
- **ICC'22** [91]. Javier Rojo, Juan Hernandez, Luca Foschini, Paolo Bellavista, Javier Berrocal, Juan M Murillo Rodriguez, José García-Alonso. Blockchains' federation for enabling actor-centered data integration. *IEEE International Conference on Communications*, pages 3430-3435, 2022.
  - GGS class (rating): 2 (A).
- **TETC** [11]. Javier Rojo, Lara Guedes de Pinho, César Fonseca, Manuel José Lopes, Sumi Helal, Juan Hernández, Jose Garcia-Alonso, Juan

Manuel Murillo. Analyzing the Performance of Feature Selection on Regression Problems: A Case Study on Older Adults' Functional Profile. *IEEE Transactions on Emerging Topics in Computing.* 2022.

  - JCR IF: 6.595.
  - Rank: Q1 26/164.

- **JCIS'22Quantum** [95]. Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo. Quantum software as a service through a quantum API gateway (Summary). *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2022.
- **JCIS'22SOWCompact** [88]. Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal. SOWCompact: A federated process mining method for social workflows (Summary). *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2022.
- **JCIS'22QSalud** [93]. Jaime Alvarado-Valiente, Javier Romero-Alvarez, Javier Rojo, Enrique Moguel, Jose García-Alosno, Juan M. Murillo. Arquitectura Orientada a Servicios basada en Computación Cuántica para farmacogenética. *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2022.
- **JCIS'22OpenAPI** [96]. Javier Romero-Alvarez, Jaime Alvarado-Valiente, Javier Rojo, Enrique Moguel, Jose García-Alosno, Juan M. Murillo. Generación de Servicios Cuánticos ampliando la especificación OpenAPI. *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)*, 2022.
- **QSE** [97]. David Valencia, Enrique Moguel, Javier Rojo, Javier Berrocal, Jose Garcia-Alonso, Juan Manuel Murillo. Quantum Service-Oriented Architectures: From Hybrid Classical Approaches to Future Stand-Alone Solutions. *Quantum Software Engineering*, 2022.
- **ISG'22** [92]. Javier Rojo, Jose Garcia-Alonso, Juan M. Murillo, Sumi Helal. Improving the assessment of older adults using feature selection and machine learning models. *International Conference on Gerontechnology*, pages 544-544, vol. 21, 2022.

Summary of Publications

Figure 1.5 shows the summary of publications carried out during this dissertation, grouped by year (columns) and topic (rows), according to the contribution themes presented in Section 1.5.1. When a publication address different topics, this has been classified according to the topic of its main contribution.

For each publication, a point was marked in the chart with different characteristics depending on: the author of this dissertation position (black = first, gray = second, white = third), the general objectives (from Chapter 1.3) associated with that publication (upper left dot = GO1, upper right = GO2, lower left = GO3, lower right = GO4), and the relevance of the publication venue (large points indicate most relevant publications, such as full papers in class-1 or class-2 conferences, and JCR journals).

As illustrated in Figure 1.5, a well-defined path has been followed during the Ph.D. with the final goal of reaching a complete and functional Personal Health Trajectory Framework. First of all, work has been done on the inclusion of information from IoT and IoMT devices in the Personal Health Trajectory. To do so, efforts have begun by investigating how to automate interactions with these devices (IWoG'19, PerCrowd'20, WCMC, JCIS'21Smart). Especially for more senior users, who are less familiar with their use. These users are the ones who most demand the care of health professionals and those who most need continuous monitoring of their health, which is affected, among other factors, by age. Following this, work has continued in this line with the definition of proposals to extract the most relevant information from the continuous dataflow generated by these devices. To this end, the use of process mining through Federated Process Mining (JCIS'21SEA, ICWE'22, IS, JCIS'22SOWCompact) has been proposed. This proposal allows mining patterns in user behaviors and generating Social Workflows based on them. This makes it possible to determine which users comply with patterns associated with a certain pathology and to search for other adjacent patterns that are also present in common in this group of people. This allows the discovery of new factors associated with the pathology, for example, and the inclusion in the Personal Health Trajectory of the presence or non-presence of these factors.

In parallel to the last steps in this line, work began on the integration and interoperability of patient health data distributed among different healthcare institutions and the same IoT and IoMT devices mentioned above. In this line, all efforts have been focused on the definition of the blockchains' federation proposal (SEH'21, ICC'22). This proposal has allowed the interoperability of data without the need for physical integration, through a two-level architecture based on blockchain: a first level where there is a blockchain per patient that allows generating their Personal Health Trajectory, and a second level with a single blockchain for the entire system that ensures access to data from the blockchains of patients from health institutions. In the last steps of the dissertation, proposals to obtain the health traceability on the Personal Health Trajectory offered by the blockchains' federation (IWoG'21) have been started working. In this proposal, it is proposed to extend FedBlocks, keeping the original blockchains' federation architecture, to record all CRUD operations performed on the Personal Health Trajectory of each patient.

In the last months of the development of the dissertation, there has also been an increased effort in the line of enrichment and interpretability of health data. We began by analyzing whether the Personal Health Trajectory data, due to its characteristic of offering a health trend over time, could be used to predict the evolution of the patient in the near future. To this end, we used the study of the functional profile of the elderly over time and obtained promising results (IWoG'20). Following this, work began on being able to select which characteristics are the most relevant for each diagnosis, in order to optimize healthcare processes and create better diagnoses with less need to collect patient health data. For this purpose, Feature Selection techniques were used. The objective was, on the one hand, to optimize the Personal Health Trajectory to store only the really important information and, on the other hand, to optimize the diagnoses. Again, the case study of the functional profile of the elderly was used to corroborate this proposal (TETC, ISG'22). In addition, work has begun on defining a framework that allows the selection of these characteristics in a way that is assisted by health professionals. This is one of the latest lines of research being worked on and is proposed as one of the main future works of this dissertation (Chapter 8).

In the line of data enrichment and interpretability, there have also been transversal publications in the area of Quantum Computing, analyzing the use of this technology as an alternative to mining health data. These data are very complex and mining them with current computing techniques can be complex (JCIS'22QSalud). Therefore, solutions have been proposed to integrate services based on quantum computing that can be consumed by classical systems to perform these health data mining tasks on quantum computers (QSET'21, QUATIC'21, IC, SQJ, JCIS'22Quantum, JCIS'22QOpenAPI, QSE).

In addition to all these publications, a first publication was also made at a Ph.D. Symposium to expose the reason for the dissertation and to get feedback on the scientific community (ICWE'20).

Table 1.1 provides a summary of the number of publications of each type done during the Ph.D. Those types that do not appears (such as non-relevant journals) means that there are not publications in those venues, even when the authors are aware of their existence.

Publication type	Number of publications
Book chapter	1
National conference	6
International workshop	6
International conference (non-relevant)	4
Relevant conference	1
Relevant journal	2
Very relevant journal	3
TOTAL	**23**

Table 1.1: Number of publications per type

1.5.3 Developed Tools

The contributions to the literature or state of the art that has been made through publications, on many occasions, had associated with them the development of a new tool. All these developed tools have been made available to the research community and industry so that their use can lead to new research or industrial developments that contribute to the same or other topics addressed in this dissertation. It is important to highlight the following list of developed tools (sorted by release date):

- **SOWCompact**[1]. SOWCompact [6, 88] is an implementation of the part running on smartphones in the Federated Process Mining architecture proposed in this dissertation for the mining of Social Workflows in a distributed architecture based on services and pervasive computing. This tool has been used for the inclusion of information from IoT devices in the Personal Health Trajectory Framework. Specifically, in the part of obtaining the relevant information from the continuous dataflow of the devices. SOWCompact is a tool ready to be used in mobile devices, allowing the mining of event logs in these devices through process mining. Specifically, through implementations of model discovery algorithms such as Alpha. In addition, it allows the query and retrieval of information from these models from remote servers. The SOWCompact publication can be found in Chapter 5, where a full-text about the research that led to the development of this tool is provided, and in Appendix O.
- **Social Events Analyzer (SEA)**[2,3]. SEA [89, 7] is the next step of

[1]`https://bitbucket.org/spilab/androidalpha`
[2]`https://bitbucket.org/spilab/individualpmmodule`
[3]`https://bitbucket.org/spilab/fpmserver`

SOWCompact, which offers a complete tool for Federated Process Mining. In addition to offering the components for data mining on mobile devices already offered by SOWCompact, it also offers the social mining part on Federated Process Mining servers and the entire communication system between the server and smartphones. Its use fulfills the same objectives as SOWCompact, with the particularity that this tool has been prepared not only to take advantage of the information from the Social Workflows on the servers. It also allows access to this information from other services or from the smartphones themselves that generate the user data, in order to generate feedback and automatic learning processes based on this information. More information about this tool and its motivations and context of use can be found in Appendices H and L.

- **FedBlocks**[4,5]. FedBlocks [8, 91] can be considered the most important tool of this dissertation. It is the one that allows the integration of health data, achieving its interoperability without a physical integration of the data. In addition, it achieves other objectives such as the standardization of the technology used for data storage, the provision of this integrated data as a Personal Health Trajectory and its access through an API that we call FedBlocks Connector. It is part of the blockchains' federation proposals of this dissertation. Its implementation is based on Python and Hyperledger Iroha, making use of private blockchains with permissions (those in which only people with sufficient permissions can read and write data) for generating and guaranteeing access to the Personal Health Trajectory of each patient. More about this tool and the research that generated it as result can be read in the publications included in Chapter 6 and in the Appendix E.

- **Quantum API Gateway**[6]. The Quantum API Gateway [13, 95] is a proposal on the use of quantum computing for the execution of services in hybrid classical-quantum architectures. This tool is included in the part of data mining. Specifically, within the study of new methods of computation for one most efficient computation way for the analysis of health data. What the tool allows is the selection of the best quantum hardware available at a given time for the execution of quantum code as a service. This service can be consumed by other parts of classical software that, for example, derive to it the more complex computational parts (such as predictions on heavy and intricate health data [93]). More details about this tool can be found in Appendices J and N.

[4] https://bitbucket.org/spilab/is_components
[5] https://bitbucket.org/spilab/fedblocks_connector_api
[6] https://github.com/frojomar/Quantum_API_Gateway

1.5.4 Research Stays

During the Ph.D., a research stay has been carried out at an international institution: the University of Florida (USA), under the supervision of Professor Sumi Helal. This research stay lasted 3 months (from March 2022 to June 2022) and allowed the doctoral student to access the international mention in his dissertation.

In this research stay, studies have been carried out in the area of Health Data AI for enriching and improving the interpretability of patient health data. Specifically, a proposal about the use of Feature Selection to determine which are the most relevant characteristics in a diagnosis and to optimize the health processes of patients' evaluation has been worked on. As a result, an article [11] was published in a high-impact journal about this topic applied to the analysis of the degradation of the functional profile of the elderly. A publication [92] in the International Conference on Gerontechnology was achieved also.

Besides the previous work, proposals for the interoperability part of the healthcare systems were also developed. Specifically, a first proposal [9] was defined to create personal health traceability by taking advantage of the integration of distributed patient data on the Personal Health Trajectory. This proposal serves as a basis for future work along this dissertation line, as mentioned in Chapter 8 of this document. Likewise, another future work of the dissertation also arose from this stay: the creation of a semi-automatic Decision Support framework based on Feature Selection and assisted by health professionals for the selection of determinants in the diagnosis of patients.

This stay has also allowed the Ph.D. student to transmit the knowledge acquired during his dissertation to the students of the University of Florida as a mentor in the Digital Health course of this university.

1.5.5 Research Collaborations

During the Ph.D., in addition to the aforementioned international stay at the University of Florida and the collaboration with Professor Sumi Helal, there has been collaboration with other national and international institutions. Not only with researchers in the area of Computer Science from other universities, but also with researchers from other areas related to health. The latter is to ensure that the results obtained during this dissertation were as faithful as possible to what is really needed by the healthcare domain of technology to solve the problem faced. In this way, the research carried out was intended to be as useful as possible for health professionals and health institutions.

Firstly, we have collaborated with researchers from the Computer Science area of the University of Malaga (Spain). Specifically, this collaboration has aimed to improve the results in the area of Process Mining for the mining of Social Workflows, collaborating with a full professor of the University of Malaga with more experience in the area: Professor Carlos Canal. This collaboration has yielded several results: a very relevant journal, an international conference paper, and two national conference papers (one of them awarded).

Secondly, we have collaborated with researchers from the Computer Science area of the University of Bologna (Italy). These researchers (Professor Luca Foschini and Professor Paolo Bellavista) have previous experience in the use of blockchain technology and in the performance evaluation of systems based on this technology. Therefore, their collaboration has been of great help to evaluate the results of the different proposals for health data integration using the blockchains' federation proposed in this dissertation. As a result of the collaboration, a relevant conference paper and another contribution submitted to a very relevant journal have been obtained. The latter is still under review at the time of writing this document.

In the area of health, we have collaborated with multiple professors of the Comprehensive Health Research Centre (CHRC) of the University of Évora (Portugal): Professor Manuel Lopes, Professor César Fonseca, and Professor Lara Guedes de Pinho. All of them have contributed to the collection of the data used to evaluate the different contributions made throughout the Ph.D. In addition, their help has been crucial in defining the objectives to be met by the Personal Health Trajectory Framework and the characteristics of the proposals to be defined for its achievement. As a result of this collaboration, several contributions of different types have arisen.

1.5.6 Grants and Awards

During the time this dissertation has been carried out, and even before it started, a series of grants and awards have highlighted its quality, helping to finance it and disseminate its results:

- **FPU predoctoral fellowship.** In 2020, I was granted the premier and highly competitive national fellowship to carry out Ph.D. studies in Spain: The FPU grant (Formación de Profesorado Universitario, in English: University Lecturer Training). These grants are assigned according to the curriculum vitae of the student, the curriculum vitae of his thesis directors, the proposed dissertation, and the research team that supports him or her. It is awarded by the Ministry of Science, Innovation, and

Universities of the Government of Spain. The grant was obtained in the first call for applications (the FPU 2019 call) when the student was still beginning his master's studies, which highlights the interest that this dissertation generated in the funding entity. The proposal submitted to this call was later published as part of a Ph.D. Symposium [1].

- **Best demo paper award in JCIS 2021.** In 2021, the demo tool's paper [89] published by the author of this dissertation in the national XVI Jornadas de Ciencia e Ingeniería de Servicios received the best demo paper award for our contributions to the application of process mining for Social Workflows in the context of pervasive and services computing.

- **Best student paper award in JCIS 2022.** In 2022, the paper [96] co-authored by the author of this dissertation in the national XVII Jornadas de Ciencia e Ingeniería de Servicios received the best student paper award for our contributions to the quantum computing and services engineering proposing new techniques for the generation of quantum services by means of Open API.

1.6 Structure of the Dissertation

This dissertation is organized into four parts, each of which is structured in chapters. The four parts are the following:

- **PART I: SUMMARY OF THE DISSERTATION**. This part contains this introduction (Chapter 1) summarizing the dissertation, and another chapter (Chapter 2) including its principal results, grouped by topic.

- **PART II: SELECTED PUBLICATIONS**. In this part, the core publications of the dissertation are included. First, in Chapter 3 the most relevant and supporting publications are listed. After that, Chapter 4 to 7 include a full-text copy of these most relevant publications. As well, a full-text copy of each supporting publication is included as appendices.

- **PART III: FINAL REMARKS**. This part is composed by a chapter (Chapter 8) where the conclusions about the dissertation are presented, together with a brief discussion about the topic of the dissertation and the results obtained, and the limitations of the contributions done to the literature in this dissertation. Future research lines are included addressing these limitations are included also.

- **PART IV: APPENDICES**. The appendices included in this dissertation contain a full-text copy of each of the supporting publications, sorted by order of publication (from Appendix A to S).

Finally, the bibliographical references of this dissertation are included.

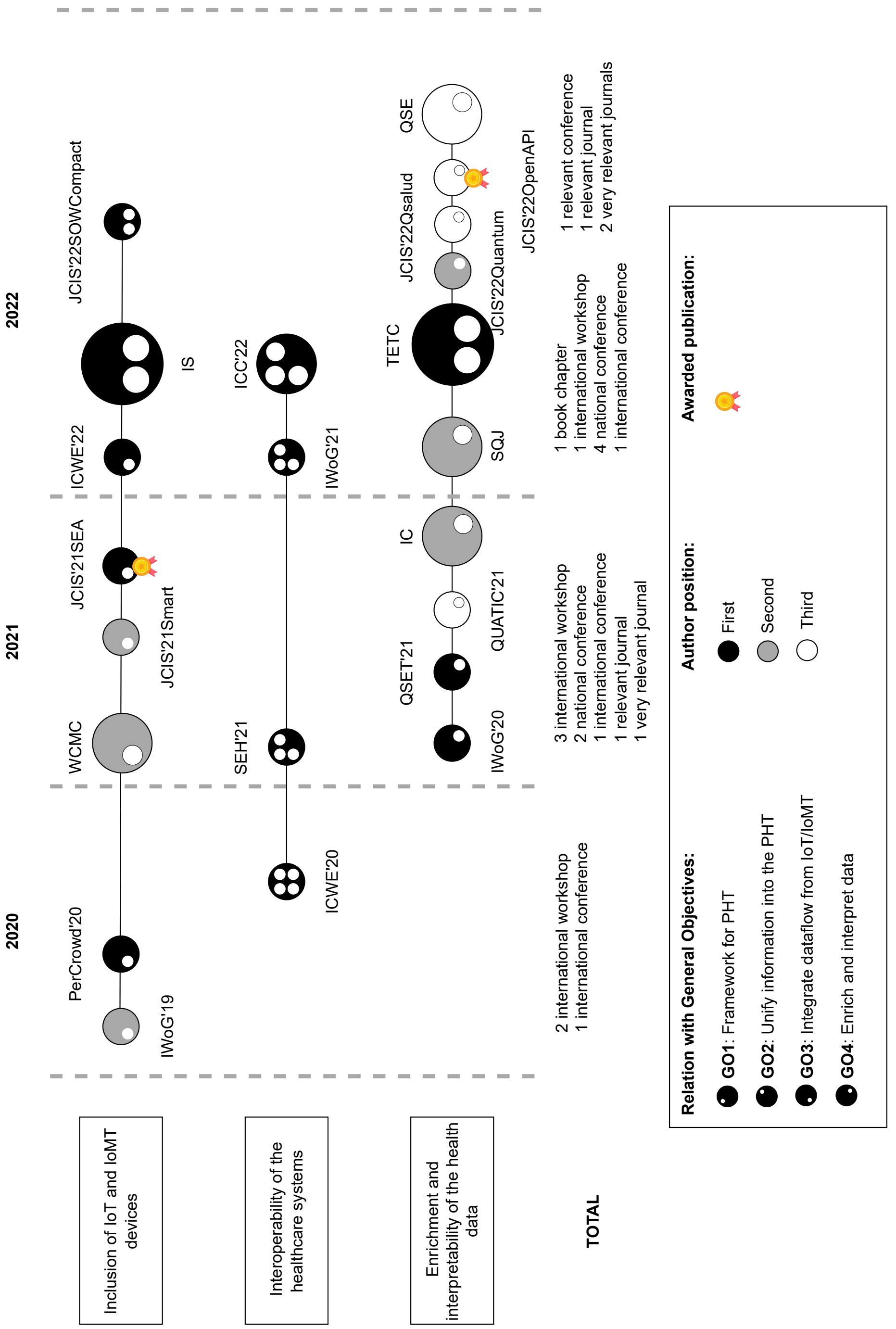


Figure 1.5: Summary of publications grouped by year and topic

Chapter 2

Results

Contents

It is better to know something about everything then everything about something

Blaise Pascal

In this chapter, we present in detail the research contributions achieved during the Ph.D. These contributions are grouped by topic. Section 2.1 addresses the contributions related to the inclusion of IoT and IoMT devices into the Personal Health Trajectory. In Section 2.2, the contributions related to the interoperability of the healthcare systems for the generation of the Personal Health Trajectory are detailed. The contributions in the enrichment and improvement of the interpretability of health data are discussed in Section 2.3.

2.1 Inclusion of IoT and IoMT devices

This section presents the different proposals made in order to mitigate the various limitations that prevent IoT and IoMT device information from being included as part of the Personal Health Trajectory. The results obtained are presented in the same order in which they were obtained, following a logical order over time, as can be seen in the following subsections.

First, a study was carried out on how to include health information that until now had been difficult to digitize, such as the taking of medication in the elderly. For this purpose, a new IoT device of the voice assistant type was proposed [3]. After this, automation of people's interactions with this and other IoT devices in their environment was sought, in order to minimize the impact of these devices in their daily lives [4]. Work continued on how to apply this proposal to nursing homes, in order to create Smart Nursing Homes where the elderly could also make use of this type of devices [5, 87]. Finally, a solution was proposed to mine the information captured by all these devices and optimize the transfer of information from devices to the Personal Health Trajectory, going from including all the continuous dataflow generated by IoT devices to only relevant information determined on the basis to that dataflow [6, 88, 89, 7].

2.1.1 ACHO: Voice Assistant to Remind Pharmacologic Treatment in Elders

The first research that was carried out within this research topic was to create a voice assistant that would allow digital medical information as important as taking medication: the ACHO assistant [3]. This information is crucial for the diagnosis of patients. Especially in the case of elders, where a large number of medications are mixed at the same time in most cases [99].

A voice assistant was chosen as this type of system has been one of the most disruptive tendencies at human-computer interaction [100] and has torn down many constraining barriers. Taking advantage of this new paradigm, elders can easily engage with devices that could help them in day-to-day situations, as long as the two challenges arising from environmental and human factors are resolved:

1. **Voice assistant at rural areas.** The majority of people living in rural environments are elderly [101], so these areas are one of the areas that may demand the greatest number of ACHO users. The biggest limitation facing any assistant that wants to deploy in these areas is that, in many

towns in this environment, access to a good quality internet connection (or even minimal access to an internet connection) may not be possible. Voice assistants intended for deployment in these environments must take this into account and be able to operate even without a network connection.

2. **Appropriate speech with elders.** Elderly users are the target audience, so it is important to keep this in mind when drafting speeches, especially when discussing medications and doses. Elders usually do not recognize drugs by name or trademark. More frequently, physical descriptors or even personal requirements, like a position inside a storage rack, are used [102]. The voice assistant must support a wide range of customization choices in this way.

To solve the first of these two limitations, ACHO was implemented using Snips[1] technology, which allows the assistant to work autonomously without an Internet connection. The second limitation was solved by adapting the device for use by elders and developing an entire platform that synchronizes with the assistant via Bluetooth. This platform allows health professionals are able to configure the voice assistant and add prescriptions and appointments. In this way, the interaction of the elderly person is limited to only having to listen to the reminders and confirm to the assistant that the dose indicated by the assistant has been taken.

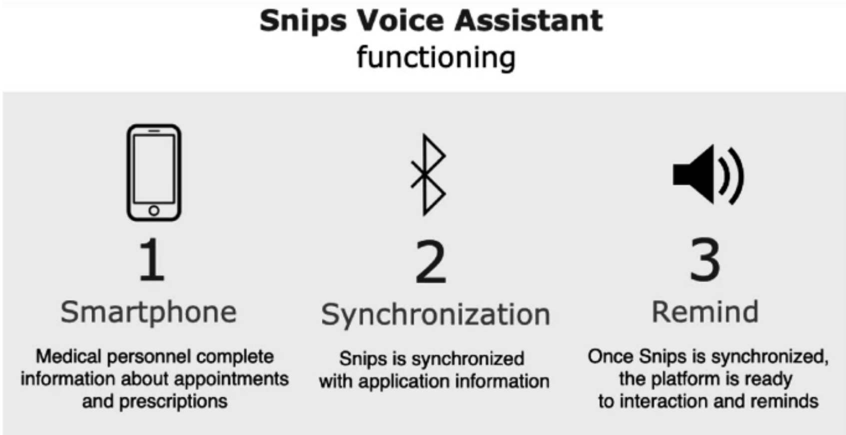


Figure 2.1: Acho overview [3]

Figure 2.1 shows an overview of the three main steps involved in the use of ACHO: (1) Elderly information configuration, (2) Snips synchronization,

[1]https://snips.ai/

and (3) Snips operation. This procedure has to be done every time a change is made in the prescriptions or appointments.

2.1.2 Automatization of IoT interactions

The next proposal within the research topic in charge of making possible (and optimal) the inclusion of IoT devices in the Personal Health Trajectory consisted of automating the actions with these devices. To do this, the use of Machine Learning and Deep Learning techniques to learn from the interactions of users with their IoT devices connected to their smartphones has been proposed. This study resulted in a proposal capable of executing automation on smartphones [4].

The main contribution of this proposal was to be able to learn precisely what action the user was interested in performing at each moment with each of their devices. To do this, instead of focusing the proposal on the relationships between devices, or on the recommendation of custom operating models for each device, as did other existing proposals in the literature [103, 104, 105], the focus was put on the context. The proposal developed allows the prediction of the behavior of each device separately (something that the last proposals tend to do [106, 107]). In this way, the manual actions that a user performs with each of her devices and all the information of the context at the time of performing these actions are recorded. With this information, the goal is to discover a behavioral pattern that guides the user in each of her interactions.

To be able to do this, the context of the device at the time of the action has been used. This context information comprises the environment in which the device is located, the type of device, temporal context, and which device is itself being interacted with. All this information is used as input to a Deep Learning model, which, based on it, determines the action that the user will want to perform in that device and context. The neural network used can be seen in Figure 2.2.

The way in which this neural network has been integrated into the users' smartphones is shown in Figure 2.3. The Deep Learning model is included in smartphones using TensorFlow Lite, after being generated in an external server by TensorFlow. Once the model is in the smartphone, it allows predictions to be made without the need for any connection to the server. Therefore, the server function is relegated to regenerating the model every time the action log is updated and sending a new version of the model to the smartphone. This is due to the software limitations imposed at the time of the study associated with this proposal (since at that time no tools capable of generating the models on the smartphone itself were found).

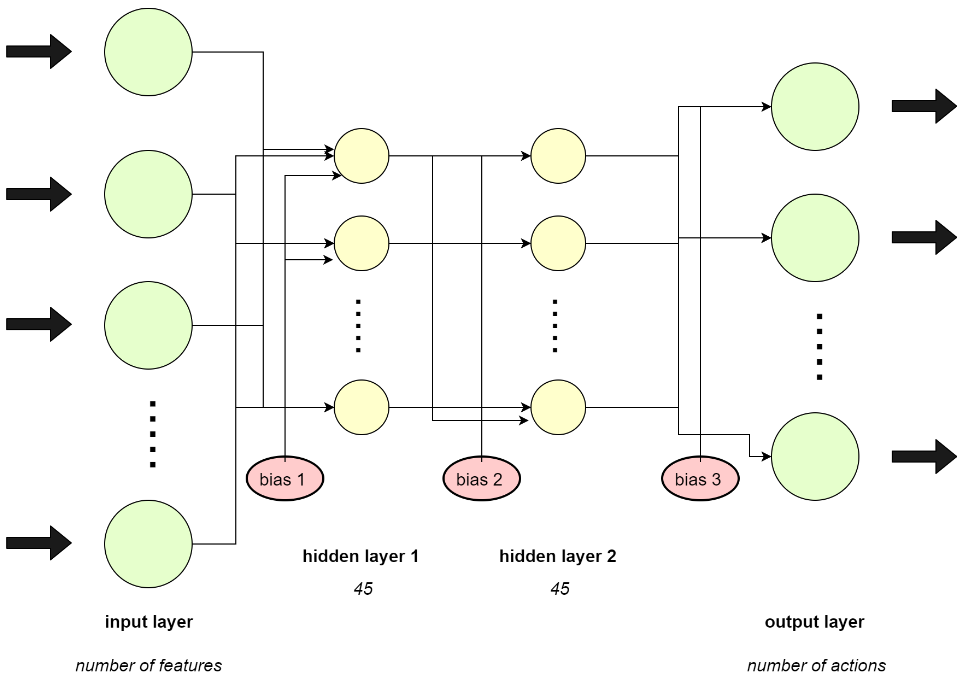


Figure 2.2: Neural network for automatization of IoT interactions [4]

In order to determine that the most interesting model to include in smartphones for IoT device automation was a neural network as described above, a comprehensive study of different non-deep Machine Learning algorithms and different configurations of Deep Learning neural networks was performed. This study was performed by generating synthetic data of interactions with IoT devices by various users in various environments over several days. These users were simulated using the TheONE network simulator, which was modified to adapt it for use in generating interactions with IoT devices.

When selecting the model with which to automate actions, not only the accuracy of the predictions was taken into account. It was also important to evaluate the time needed for the model to predict interactions, as well as the time needed to update the model with new behavioral changes.

To validate the proposal, an application was developed where users could manually register actions with their IoT devices. The application automatically took the context information of that moment and added the action to an action log with all the actions of all the devices of that user. After that, it started to generate the prediction model using this data. When the reliability of the model was sufficient, it began to automate the actions, allowing the user to correct those that were incorrectly predicted or those for which the behavior had changed. These corrections or changes were annotated by the

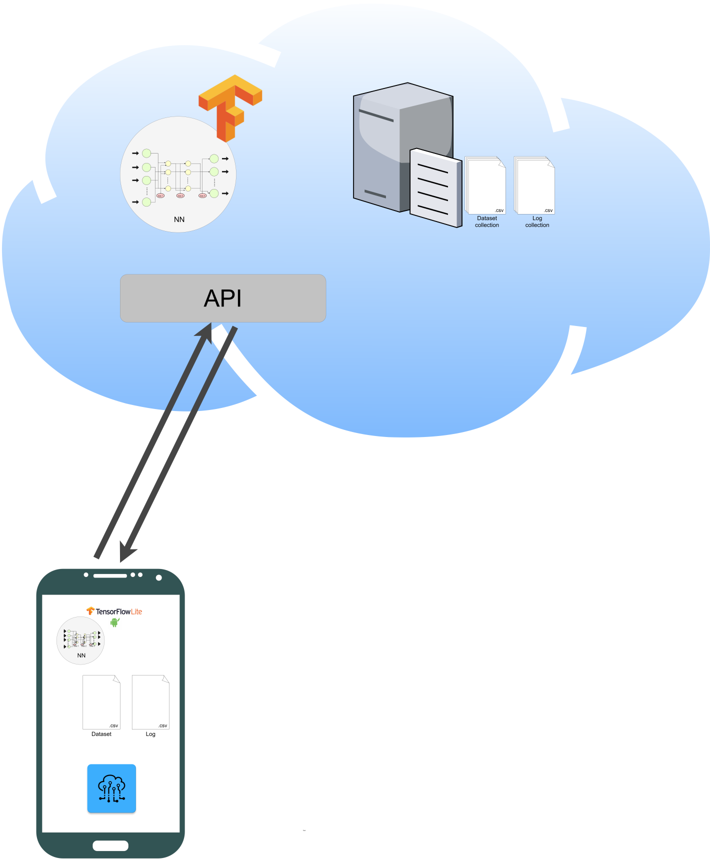


Figure 2.3: Architecture for automatization of IoT interactions [4]

application to help the model modify its behavior toward the correct one.

This application was used in five different persons with completely different routines, assuming five different performance scenarios. Thanks to this, it was verified that the proposal, using a single model for all types of environments (with many or few devices) allows us to obtain good predictions of interactions with devices, based only on devices and context-awareness information. With a training period of only two weeks, and collecting data on how accurately 573 predictions had been made during the following week, we obtained an accuracy of between 76% and 92% of successes (automated actions that were not subsequently corrected by the user). This range was determined by whether the user showed a greater number of patterns in her behavior or, on the other hand, showed a chaotic behavior where it was difficult to find patterns to automate her actions.

It has been studied the use of a threshold to automate actions only when the model was sufficiently confident that the predicted action was correct, thus discarding the automation of actions for which the model was not really sure it was able to automate them. This threshold allowed us to observe how its use could prevent only 8 of the 84 incorrectly performed automation from being incorrectly performed. The other 76 were actions that did not follow an apparent pattern, so they were below the threshold because they were impossible to predict (for example, trying to predict which TV channel a user will want to watch on his smart TV at night when every night he plays a different one).

2.1.3 Smart Nursing Homes

The next step was to develop a proposal that would allow the use of IoT devices by elderly people living in Nursing Homes. To do this, a system was developed that, again using Deep Learning, allowed the creation of Smart Nursing Homes where the actions of the elderly with IoT devices were automated [5, 87].

The proposal presented in this work is aimed at taking advantage of the benefits that the IoT offers in combination with machine learning algorithms to monitor people in order to detect pattern behaviors and to predict future actions in nursing homes with no or intermittent Internet connection. This is achieved by developing an architecture that integrates different sensors and actuators in nursing homes to improve the monitoring of elderly people and the processing of the gathered data by these devices. To favor multi-device environments and give users the freedom to use different types of sensors and actuators, the architecture is capable of working with WiFi, ZigBee, and Bluetooth (among others) communication protocols. Furthermore, the correct behavior of this architecture does not depend on Internet connectivity as it is designed to work in rural areas with limited or no Internet connections. As previously discussed, the majority of people living in rural environments are elderly [101].

Although the proposal is designed for environments with a limited Internet connection, it can be implemented in places where the connection is stable such as nursing homes located in smart cities, where there is a growing awareness of intelligent devices and they are being incorporated into people's daily lives.

The proposed architecture (Figure 2.4) consists of three main parts:

- **Inputs**: The inputs represent those devices that can provide information about the environment, people's smartphones that can be used to track their locations within the nursing home or frequent interactions with other devices (and to provide contextual information about the person

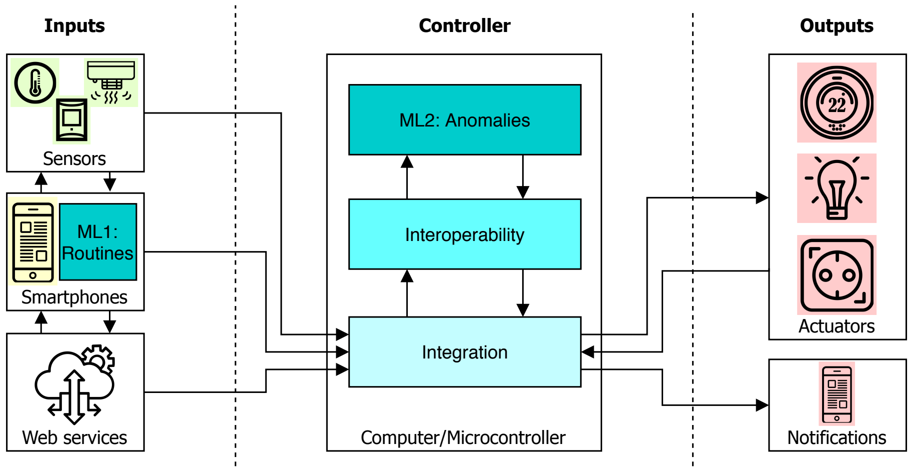


Figure 2.4: Architecture for Smart Nursing Homes [5]

employing the different sensors they posse), and web services that provide additional information about the seniors' residence. Smartphones process this information for each user to detect patterns of behavior and automatized the action performed later with outputs.

- **Controller**: The controller, which can be from a simple Raspberry Pi to a dedicated server, processes the information coming from the different sensors and smartphones (inputs) to interpret it. The controller consists of three main components. The first component, *Integration*, is responsible for ensuring proper integration among the different devices (sensors and actuators). Once the devices are integrated, the *Interoperability* component is responsible for ensuring collaboration among the devices. The last component of the controller, *ML2 Anomalies*, is responsible for processing the information collected to detect possible anomalies in people's behavior.

- **Outputs**: The outputs represent the actuators that are in charge of triggering different actions depending on the information that has been previously processed. These actions will vary depending on the type of actuator.

To generate the Deep Learning model used within the controller for the automation of actions, the knowledge acquired in previous research in the automation of interactions with IoT devices was used [4]. Given the similarity between the context information that could be collected in both cases, the same Deep Learning model was taken, using the same architecture for the neural network definition. In addition, an anomaly detection model was included to analyze the manual actions of the elders with their devices and determine if there was a behavioral change (anomaly) in them. If so, their caregivers could be alerted. This model is also based on the use of specific Machine Learning techniques for anomaly detection.

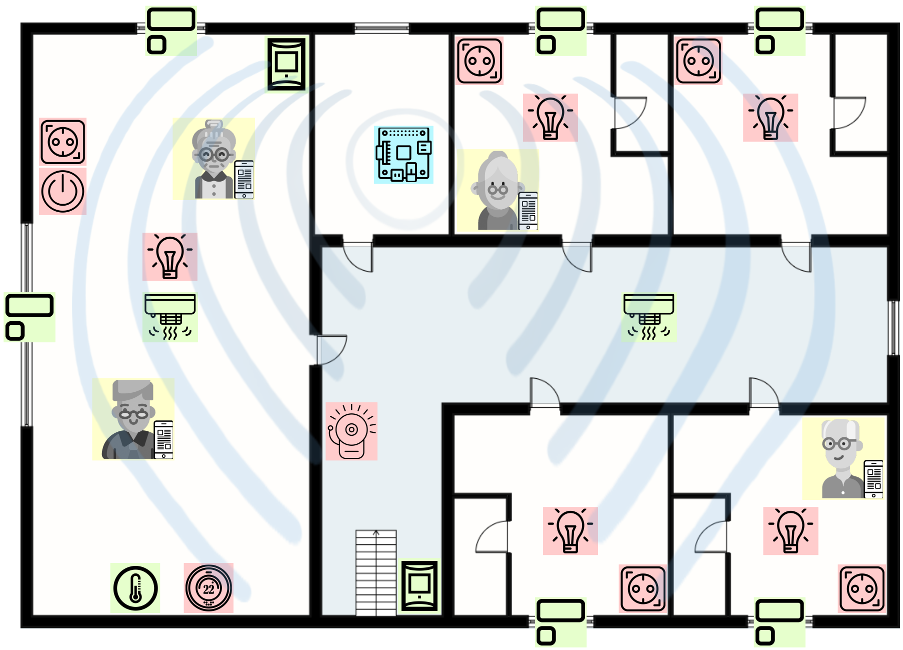


Figure 2.5: Case study for Smart Nursing Homes [5]

In this case, the application of the proposal to a specific case study was also carried out. Specifically, five elders were again taken to interact with different devices and sensors installed in the same nursing home. The list of devices can be seen in Table 2.1. The distribution of these devices across the nursing home where they were installed is shown in Figure 2.5.

The results obtained were similar to those obtained in the research on the automation of IoT devices. It was demonstrated that it was possible to automate actions to deal with the problem of automating environments to make everyday tasks easier for the elderly, through the use of smart IoT devices and machine learning techniques. New lines of research were also opened as a result of incorporating these device automation techniques in social and/or collaborative environments, where there may be conflicts at a given time about the action that two different users want to perform with the same device.

Device	**Supported protocol(s)**	**Description**
Controller		
- Raspberry Pi 3 Model B+	WiFi/Bluetooth/ZigBee	The controller to manage the environment
Sensors		
- Motion sensor Xiaomi	ZigBee	To detect movement
- Temperature/Humidity Xiaomi	Bluetooth	To control the temperature and humidity
- Doors/Windows closed Xiaomi	ZigBee	To detect when a door or window is opened
- CR Smart Home Smoke Xiaomi	ZigBee	To detect smoke/fire
Actuators		
- Xiaomi Yeelight Color V2	WiFi	Bulbs to illuminate rooms/corridors
- Smart Plug Zoozee	WiFi	Plugs to control electrical devices
- Google Nest	WiFi	Thermostat to control the temperature
- Smart Switch Xiaomi	ZigBee	Button to trigger different actions
- Xiaomi Aqara Gateway	WiFi/Bluetooth	Alarm to trigger notify emergencies
Smartphones		
- Xiaomi Mi 9	WiFi/Bluetooth	Elder's daily data
- Huawei Mate 20	WiFi/Bluetooth	Elder's daily data
- Moto Z	WiFi/Bluetooth	Elder's daily data
- Honor 9	WiFi/Bluetooth	Elder's daily data

Table 2.1: Selected controller, sensors, actuators and smartphones for the case study on Smart Nursing Homes

2.1.4 Federated Process Mining and SEA

Once it was possible to automate actions with IoT devices to make it easier for users to start using these devices more continuously, the next step was to be able to extract relevant information from the continuous dataflow generated by these devices (to be integrated into the Personal Health Trajectory together with or instead of the raw information). To this end, a proposal that allowed the analysis of whether a user presented certain patterns in their behavior with the devices was started to be studied. The behaviors to be searched for are determined by health professionals and will be of interest because of being known as the cause of a specific clinical condition or pathology in a specific group of users. The behavior of this group of users constitutes a Social Workflow that should be analyzed by means of techniques such as process mining and, within this, more specifically by model discovery techniques.

However, as the classic process mining techniques do not allow determining when a user presents a behavior of interest or not before including his information in an SOW, it became necessary to look for new ways of analyzing user information. To address the challenges of classic process mining techniques when analyzing complex SOWs resulting from integrating data from users without a common behavior pattern, the Federated Process Mining (FPM) method is proposed [6, 88]. In this method, process mining is performed in two steps: First, individual mining; then, mining user groups with common behavior. The first step allows individuals to be filtered to determine those who comply with the behavior of interest in an SOW. Once the individual data is filtered out, only the SOWs resulting from users who meet the desired behavior are analyzed.

Federated process mining uses the computational power of the users' devices to perform the first phase, which reduces the amount of data that needs to be processed to analyze the SOW. Owing to this filter, Federated Process Mining techniques offer more compact models without loss of quality.

The architecture under Federated Process Mining (Figure 2.6) is based on three main components:

- The **individual process mining** component, which integrates the traces of an individual in her smartphone and produces the corresponding behavioral process model.
- The social process mining component, which selects the users to be analyzed based on the presence of a certain pattern in their behavioral process models. Once it obtains the information of the users that meet the pattern, mining is performed to obtain the process model for the SOW that these users represent
- The Federated Process Mining aggregator (FPM aggregator) component supports the connection between these two components, asking smartphones for the individuals possessing the frequent pattern in their behavioral models and collecting their traces for the social process mining

component. This communication is performed using a query language that can be interpreted by both components.

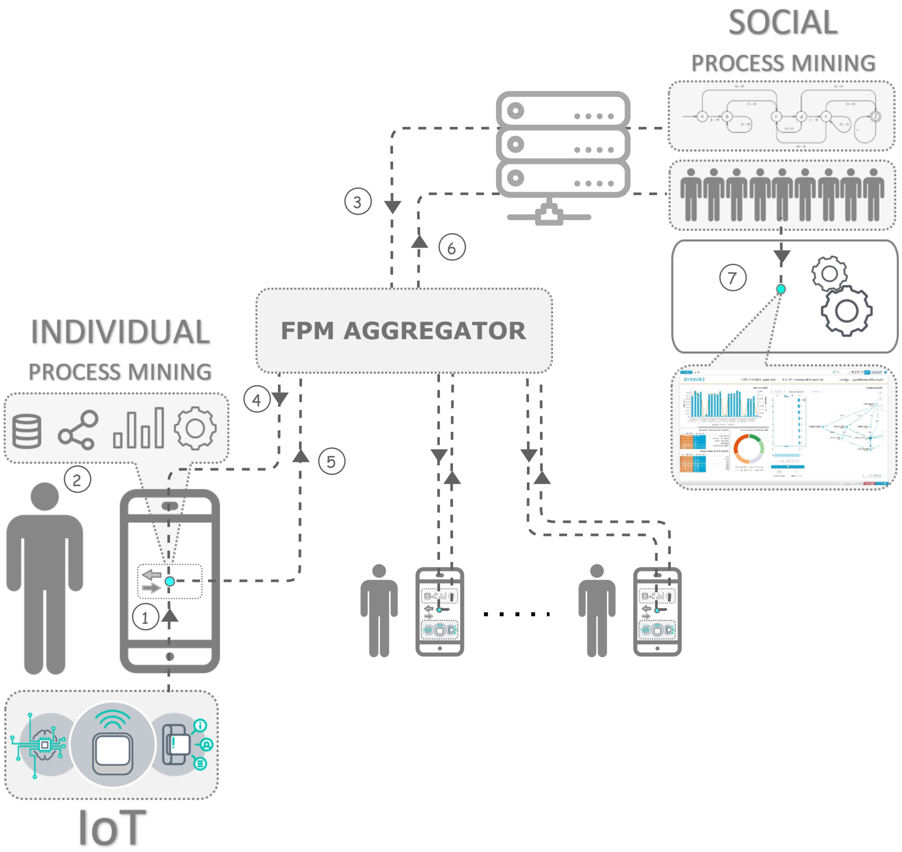


Figure 2.6: Architecture of Federated Process Mining [6]

The workflow (understanding as workflow the list of steps followed during Federated Process Mining and not the Social Workflows) presented in Figure 2.6 is described as follows:

1. An event log is produced by the user's smartphone by collecting information from sensors or applications. This stage can involve gathering user data from the smartphone, such as movement data from the GPS, activity levels from the accelerometer, application usage events, or WIFI connectivity. A module to create this log must be implemented by the programmers of the apps that make use of Federated Process Mining.

2. The user's smartphone uses this event log to run a process mining algorithm that creates a model of the user's behavior as it is recorded in the event log.

3. After this model is generated, the server can start to request data from the user event log. To do this, the server creates a query with a pattern (frequent or not) that the user models it will be collecting data from must satisfy. The FPM aggregator sends this query to all users' smartphones.

4. When the query is received in the smartphone of a user, it evaluates the model of the user to see if it matches the pattern. If so, the smartphone analyzes the event log to choose the precise traces that fit the desired pattern. Because this would be inefficient for big event logs or if queries with various behavioral patterns were regularly sent, traces are not handled immediately.

5. The query and user to which each matching trace corresponds are submitted to the FPM aggregator together with the matching traces. The data from several users' traces that satisfy the query pattern are combined by the FPM aggregator.

6. The combined data are stored in the server.

7. A new stage of process mining is conducted using these combined data. A new model describing the behavior of a single social group (SOW) is obtained in this next phase.

Using this Federated Process Mining architecture, a first reference tool was implemented to test its feasibility: SOWCompact. SOWCompact offers an Individual Process Mining module ready to be included in applications developed for Android. This module (Figure 2.7) is responsible for analyzing event logs stored in the application in question in XES format [108]. For this purpose, it implements the Alpha model discovery process mining algorithm. It also implements the necessary technologies on the mobile side to perform all communications between the server and smartphones.

In addition to this, SOWCompact offers an implementation of a process mining server using the Python tool PM4PY[2], which can be used as a Social Process Mining component in the Federated Process Mining architecture. The FPM Aggregator is implemented as part of the latter component and the Individual Process Mining component. For communication through it, a subset of the Linear Temporal Logic (LTL) [109] sufficient to establish pattern communication to test the feasibility of the proposal is used.

This tool was applied to a case study in Activity Daily Living (ADL) with the information of 7 different users who recorded in a daily event log 20 different types of actions in their daily lives. With this, it was determined

[2] `https://pm4py.fit.fraunhofer.de/`

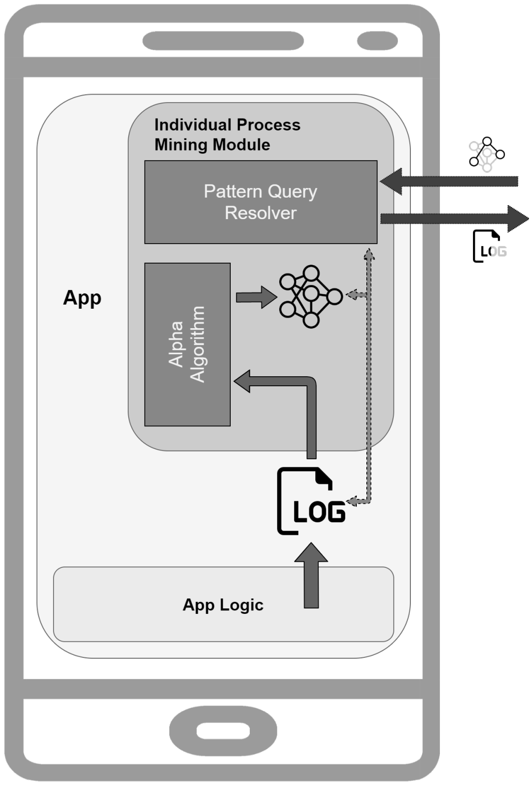


Figure 2.7: SOWCompact Individual Process Mining component [6]

that SOWCompact allowed to analyze the SOWs of these users in a more efficient way, achieving more compact, more readable and quality-preserving models. In addition to other improvements such as the optimization of server computation or the reduction of the amount of information sent to the server by users (with the consequent improvements in privacy for users).

SEA: Social Events Analyzer

A more complete tool was developed on Federated Process Mining: Social Events Analyzer (SEA) [89, 7]. SEA is a tool for developing applications that use Federated Process Mining to analyze its event data in a variety of ways. To do so, it offers all the Federated Process Mining components ready to be included in smartphones and servers involved in the Federated Process Mining process. However, the main difference with SOWCompact is that it has more efficient communications and allows the analysis of SOWs not to be performed visually on Social Process Mining servers. SOW information can be accessed through an API by other services or even by the smartphones of the users whose information is being mined. In this way, the integration of this information into the Personal Health Trajectory is facilitated automatically, once the patterns that must be periodically consulted in the users' behavior are defined.

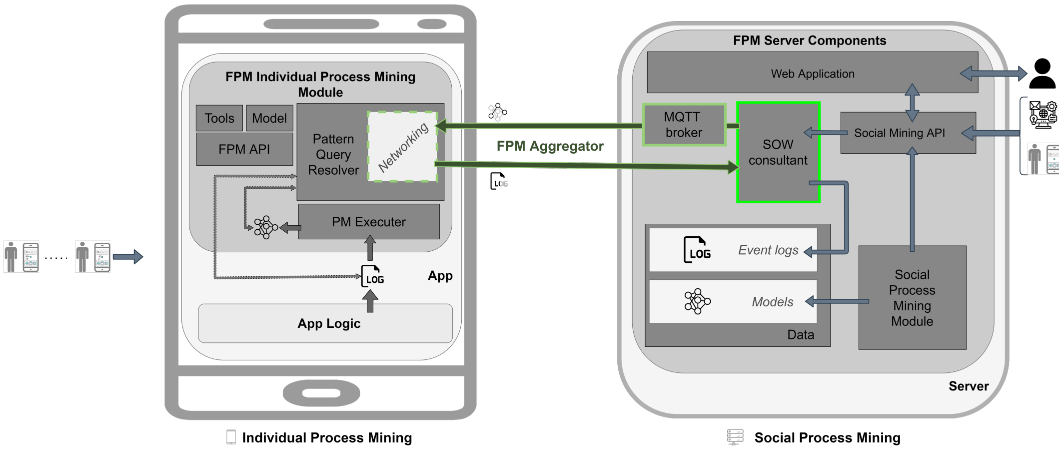


Figure 2.8: Architecture of Social Events Analyzer [7]

SEA was applied to the previous case study of IoT devices that was used for the automation of interactions with IoT devices [4]. The interactions with these devices were recorded as events (Figure 2.9) of an event log, allowing their analysis using process mining techniques. As a result, their use was shown to be appropriate for this case study and could benefit the inclusion of this type of information in the Personal Health Trajectory.

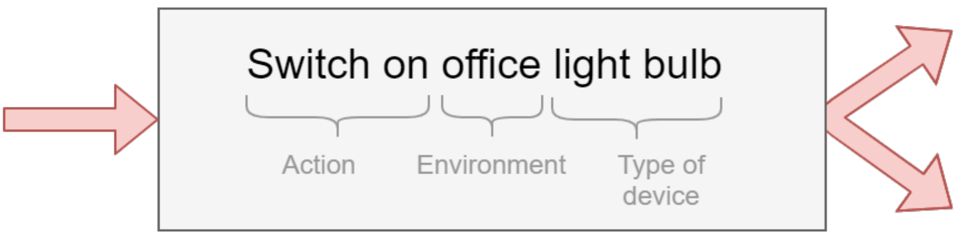


Figure 2.9: IoT event modeled for SEA

2.2 Interoperability of the healthcare systems

This section presents the different proposals made in order to obtain the interoperability of healthcare systems from institutions and devices. This interoperability allows to the integration of all health data of each patient into her

Personal Health Trajectory and offer it through the Personal Health Trajectory Framework. As in the previous section, the results obtained are presented in the same order in which they were obtained, following a logical order over time.

First, a study was carried out on how to interoperabilize a patient's health data that are distributed in different information systems without the need to reach an accurate integration of the data. That is, without the need to move the data from the information system where it was originally stored to a new information system where all the data is stored. For this, we have developed a blockchain-based proposal that interoperates the data through a proprietary concept that we call blockchains' federation and the use of web services [8, 91]. This proposal, in addition, allows make data integration independent of the storage technology used and offers the Personal Health Trajectory of each patient through an API, solving other parts of the proposal of this dissertation beyond the mere integration of the data. After this, this proposal has been extended to obtain the concept of Personal Health Trajectory Traceability [9].

2.2.1 Blockhains' federation

The existent proposals to achieve the integration of heterogeneous health data into a global view of the patient have unresolved issues around them. For example,the definition of who should keep this data structure alive and who should manage the access to it [35], making difficult to keep the global vision always up to date and for institutions to use it in the assessments of the patient. As well, none of them provide an easy and well-defined procedure for the development of software aware of the global health reality per patient that they offer. In other words, they do not offer an easy way of developing patient-centered healthcare software. These proposals are limited to creating a structure where all patient information is organized and allowing it to be manually read into it.

In this dissertation, a solution based on the use of the new blockchains' federation concept and web services, for unified access to distributed health data grouped by patients, has been proposed. This proposal is able to solve the problems of the actual integration proposals. For that, the concept of blockchains' federation applied to the health domain has been defined, and later it has been employed for the definition of one architecture. This architecture offers unified access to data, as well as promotes developers of health applications and systems (e.g., personal health applications or healthcare institutions' systems) that can use the Personal Health Trajectory of the patients as the data source on them.

The concept of blockchains' federation (Figure 2.10) refers to the usage of multiple blockchains for managing data of a system following a two-level infrastructure. In this way, in blockchains' federation, several lower-level blockchains can be interconnected using another blockchain at the top, the main blockchain, which is in charge of nesting them and providing access to all lower-level blockchains. The key to this federation lies in the fact that access to all lower-level blockchain data is achieved jointly, while these last blockchains maintain their autonomy, as do the institutions and services that generate the data. In this case, the lower-level blockchains are used to generate the Personal Health Trajectory of the patients. Each patient has a lower-level blockchain where her complete Personal Health Trajectory is generated. The main blockchain is shared by all healthcare institutions to ensure that their health professionals will always be able to access the data of any of the patients of these institutions that integrate their patients' data.

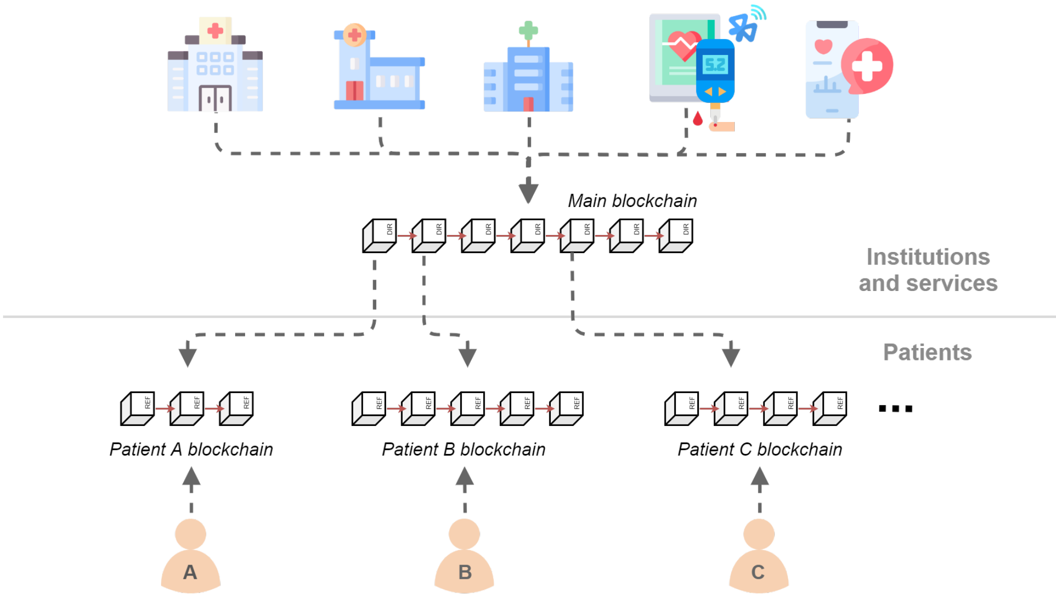


Figure 2.10: Blockchains' federation applied to health domain

Making use of the above-presented concept of blockchains' federation, an architecture that combines it with the usage of web services has been defined to generate the Personal Health Trajectory of patients while the autonomy of institutions and services producing data remains. Figure 2.11 presents a visual representation of the components of the proposed architecture and their connections. The actors interacting with it are the health professionals of the health institutions involved in the system, the own patients to which data belongs, and their smart devices. The information systems providing data that is integrated by this architecture are those of the health institutions and the smart devices' services. The full explanation of this architecture can be found in Chapter 6 [91] and Appendix E [8].

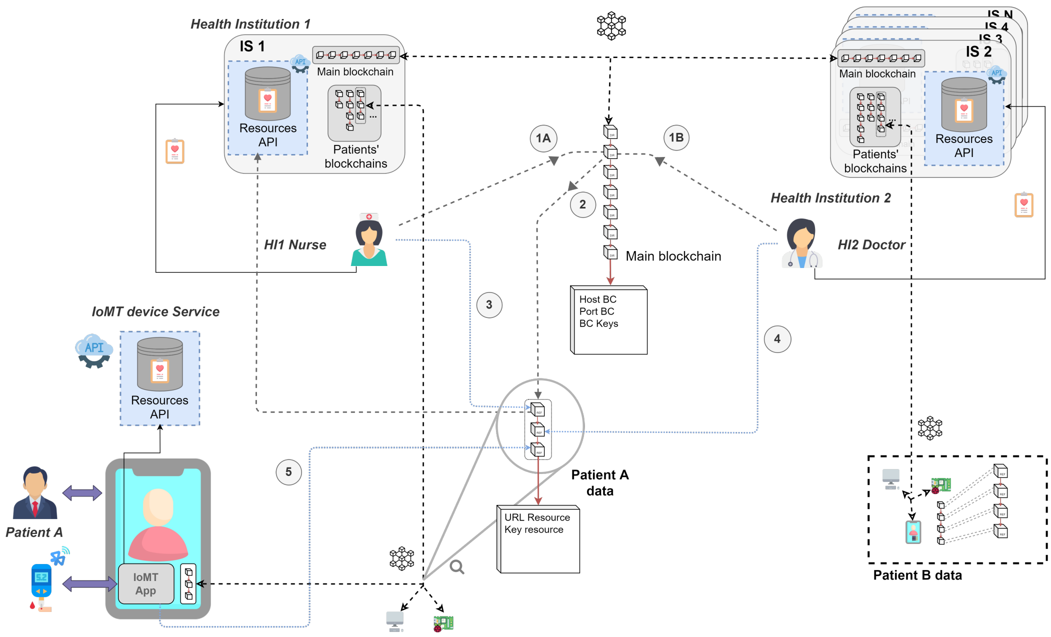


Figure 2.11: Architecture for data interoperability based on blockchains' federation and web services

As a reference implementation of this proposal, FedBlocks was developed. It offers the components for the information systems of health systems; as well as some additional components for enhancing the developers' experience developing healthcare software that employs our proposal as the data source: Personal Health Trajectory-aware software. This is the FedBlocks Connector and its REST API. It allows the development of Personal Health Trajectory-aware applications and systems that do not need of having local copies of the blockchains, making it easy to integrate the proposed solution into any kind of device without space and computational load of blockchains' nodes. For this, it provides a connector with which external health applications can connect to consume Personal Health Trajectory health data. This connector works as a smart contract, reflecting which and how the operations must be done with the blockchain.

Blockchains and Health Resources APIs are deployed in the information systems of the institutions that integrate their patients' data. The Resources APIs can be deployed also in smart devices' services. FedBlocks Connector must be deployed along with the healthcare applications.

Enabling development of Personal Health Trajectory-aware software

Together with the connector that allows the development of Personal Health Trajectory-aware software, a well-defined procedure for the development of this type of software has been defined. Figure 2.12 provides the basic diagram of connections that any Personal Health Trajectory-aware application must have with the components of the proposed architecture—some deployed in the own application and others in the information systems from institutions and services integrating data from their patients.

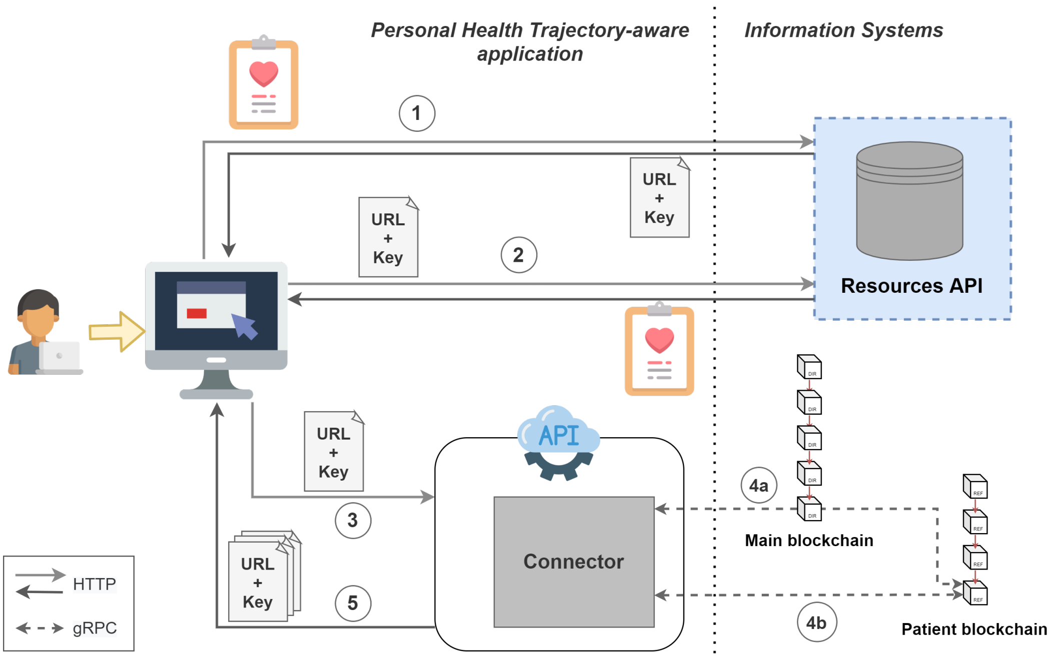


Figure 2.12: Personal Health Trajectory-aware software methodology [8]

To make easier the development of Personal Health Trajectory-aware software, applications of this type only directly interact with two components of the architecture: Health Resources APIs (or alternative storage system if selected) and FedBlocks Connector (or FedBlocks Connector REST API); being unaware of the existence of blockchains. As can be seen in Figure 2.12, FedBlocks Connector abstracts it from the usage of these components.

On the one hand, an application of this type interacts with the Health Resources APIs (connections at the top of Figure 2.12) if no information system has chosen a different storage method for the storage of the records. First, it interacts with this component when an actor of the system is saving a record in the Health Resources APIs of her corresponding information system (*1*).

In this case, the application sends a record and the Health Resources API returns the URL and key to access it. Second, the application interacts with this component to retrieve records from patients stored on it (*2*). For this, the application executes a GET operation from the URL where the record has been indicated to be stored, with the key as the Authorization header. In which of the several Health Resources APIs is stored a record is determined by the URL, so this is transparent for the application. In response to this petition (if the URL and key are correct and correspond between them) the Health Resources API returns the record, in the same format it had been sent to it. The records can be retrieved from any Health Resources API, but the process of adding a record must only be performed on the Health Resources API of the information system to which the application has granted access. For example, in the case of a doctor's application, the records are added to the Health Resources API of the institution to which the doctor belongs. In this way, the records remain stored in the institution or service that generates them.

On the other hand, the applications of this type interact with the FedBlocks Connector (connections of the lower part of Figure 2.12). For this, they must include it as part of the application or deploy the FedBlocks Connector REST API as an additional service that applications consume (as in the figure). Applications must send to it the information provided by Health Resources APIs in the operation of the step *1* to be written in the blockchain of the patient to which it belongs (*3*). In case the FedBlocks Connector was configured to interact with the main blockchain (because this application is an application for health professionals) the identifier with which the patient's blockchain was associated in the block of the main blockchain referring to that patient must be sent also. When the connector receives that information, it has to perform a read operation on the main blockchain to locate the patient's blockchain, and, later, a write operation on it to store the information of the record (*4a*). For this, the FedBlocks Connector must have been previously configured with the address and private key of the main blockchain node with which it will operate, normally that of the information systems of the institution or service to which the application belongs. In case the FedBlocks Connector was configured to interact directly with the blockchain storing the Personal Health Trajectory of a patient (because this application is an application for patients or for their IoMT devices) the identifier of the patient to which this record belongs must not be sent (having associated the patient's blockchain directly to the FedBlocks Connector it not beforehand who the patient is). However, in this case, it is necessary to previously configure the FedBlocks Connector with the address and the private key of the patient's blockchain node with which it will operate. This way, the FedBlocks Connector will connect directly to this blockchain (*4b*), without going through the main blockchain.

Apart from writing new references to records into the Personal Health Trajectory of a patient, the FedBlocks Connector also allows retrieving the existing ones. This is performed in the same way that the writing operation, but, in this case, it is not necessary to send information of a new reference to the FedBlocks Connector. Only it is necessary to send the identifier of the patient, in case of FedBlocks Connector was configured to work with the main blockchain. That is, in case it was configured to work only with the Personal Health Trajectory of a patient, this is not necessary. When the FedBlocks Connector locates the patient's blockchain (across the corresponding version of step 4), instead of writing on it, all the references writing on it are read and returned from the FedBlocks Connector to the application (*5*).

If an entity develops several Personal Health Trajectory-aware applications or systems that interact with the architecture across the same node of the main or patient's blockchain, the more interesting option is to deploy the FedBlocks Connector as a web service and employ this FedBlocks Connector REST API with all the applications. If several applications are developed associated with a system, but each one consumes information across different main blockchain nodes or different patients' blockchains, several versions of the FedBlocks Connector or FedBlocks Connector REST API must be included or deployed for communication with the system.

2.2.2 Personal Health Trajectory Traceability

Proposals integrating distributed data from different health systems in a patient-centered way usually do not address the security issues arising from it [35]. Although they offer the ability to integrate the data and allow all the agents involved in this data to operate with it, they have not implemented mechanisms that imply the security improvements that such an environment needs.

Several proposals have emerged to solve the security problems of health data, even in distributed environments, but none of them has focused on keeping the traceability of the information. They only limit their application to the implementation of security mechanisms that force the user to identify herself to interact with the data or similar solutions but do not offer real traceability, as is done in other domains, such as food's traceability [110, 111] or agricultural supply chains [112].

To solve this, the concept of Personal Health Trajectory Traceability (PHT.2) has been defined [9]. This PHT.2 look for the traceability of health data by having a registry of changes in the patient's health reality, rather than just as a directory to access their data. This registry helps the patient to have greater control over their data, to validate the authenticity of the assessment data (detecting additions, modifications, or undue deletions of data), and to have complete traceability of the patient's health reality.

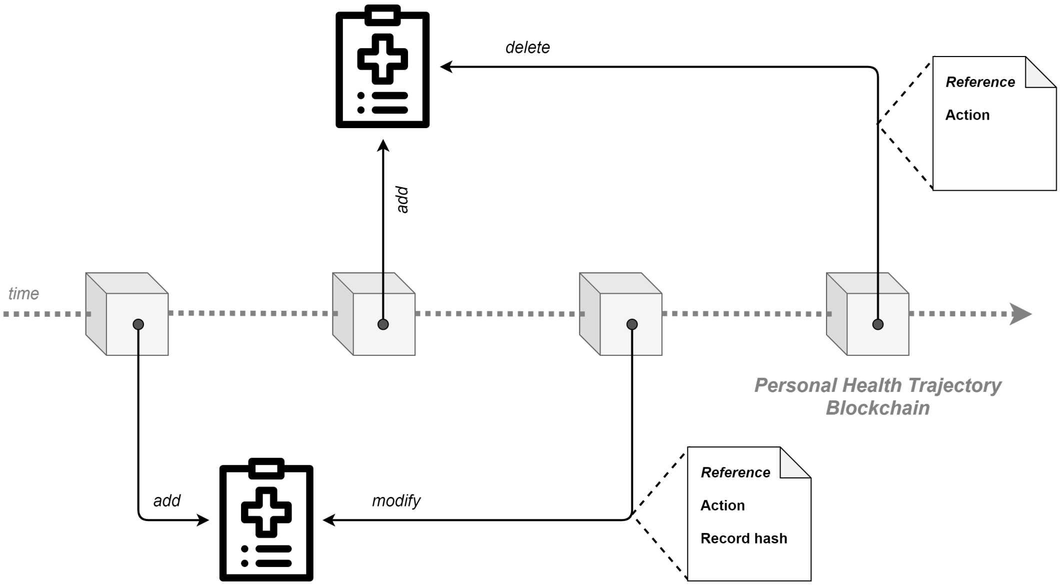


Figure 2.13: Concept of Personal Health Trajectory Traceability on blockchain [9]

PHT.2 revolves around the use of a blockchain (Figure 2.13) where a block is added to the chain for each CRUD operation performed on a health record. Figure 2.14 shows the proposed architecture for PHT.2. Each patient must have her own blockchain, as in blockchains' federation, so that traceability is generated individually for each patient's health data. That simplifies the management of each patient's traceability and being able to empower the patient by giving her permission to perform this management. In addition, it allows all operations performed on a patient's health data without being notified to their PHT.2 to be invalidated, ensuring that no data can be maliciously generated for the patient and mistakenly considered as genuine.

2.3 Enrichment and interpretability of the health data

This section presents the different proposals made in order to enrich and improve the interpretability of the health data integrated into the Personal Health Trajectory of patients by means of the Personal Health Trajectory Framework.

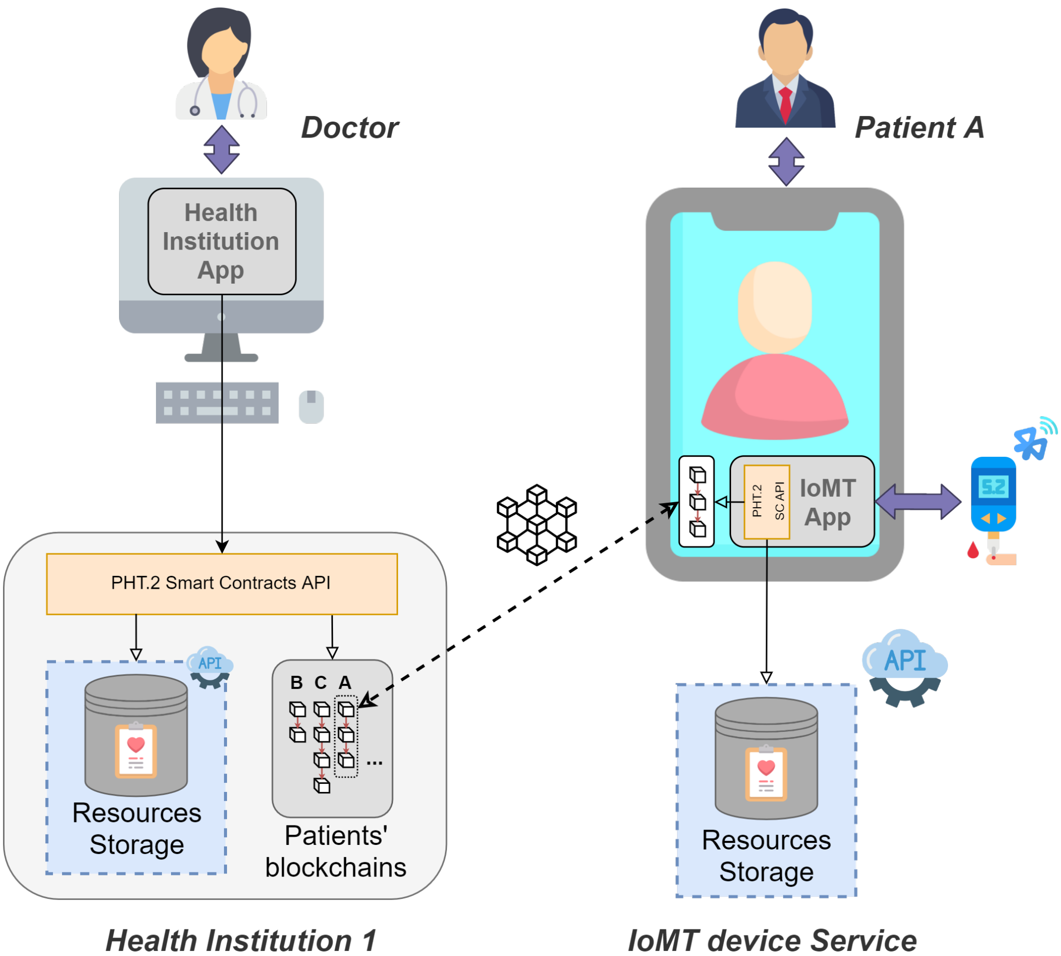


Figure 2.14: Architecture proposed for Personal Health Trajectory on blockchain

This enrichment allows obtaining new knowledge about the patient's health. The improvement in interpretability of the data allows to perform better diagnosis and improve the healthcare processes. As in the previous section, the results obtained are presented in the same order in which they were obtained, following a logical order over time, with the exception of proposals in quantum computing. The latter has been developing in parallel with the rest.

First, a study was carried out on using the Personal Health Trajectory data in the format of the temporal progression of health to predict the patient's future evolution [10]. The decrease in the functional profile of the elderly was taken as a case study. After this, work started on proposals based on the use of Feature Selection to detect which were the determinants for identifying a clinical condition from the whole set of information used in a health assessment.

Firstly, a study on the use of these techniques in health regression problems was published [11], again taking the functional profile of the elderly as a case study. Work has also begun on proposals for the creation of Feature Selection-based Decision Support Systems (FS-DSS) for health professionals. These latter studies have not yet had their results published at the time of writing.

At the same time, work has been done to start applying quantum computing to health data analysis as a service within the current classical computing systems. To this end, multiple proposals have been developed for the creation of quantum services in hybrid quantum-classical environments [94, 12, 98, 95, 93, 96]. As a result of these, a new one about the definition of an API Gateway designed for use in these types of hybrid quantum-classical systems has also emerged: the Quantum API Gateway [13].

2.3.1 Forecasting of Personal Health Trajectory

The organization of the patient's health information as a history in this situation makes it possible to conduct additional analyses on the data [46]. For instance, it would be difficult to analyze a patient's progression without having access to all of their prior data. However, having all of it integrated into the Personal Health Trajectory opens the door to these analyses.

In order to perform this type of analysis, a deep learning model has been proposed in one of the studies carried out during this dissertation [10]. This model allows the prediction of the future evolution of patients based on the data from the evolution of the patient until now and the evolution of other similar patients. The information employed for training this model is the already known evolution of patients modeled as time series.

For their implementation, a long short-term memory (LSTM) neural network has been employed, following the structure shown in Figure 2.15. This figure shows the inputs and outputs provided to the model. Specifically, the model takes as input the values per each parameter measured in the last three evaluations of the patients. As output, it returns the next value predicted for each of these parameters. This process can be replayed as time as necessary, even using the predicted values as input, to continue forecasting the evolution of the patient in the far away future (with the risk of decreasing the precision of the predictions).

This study was developed only to test the feasibility of this type of proposal. The aim was not to obtain the best accuracy. However, it was intended to demonstrate that this type of proposal could be carried out and became more feasible by having all the information integrated into the Personal Health Trajectory. To develop the study, the analysis of the functional profile

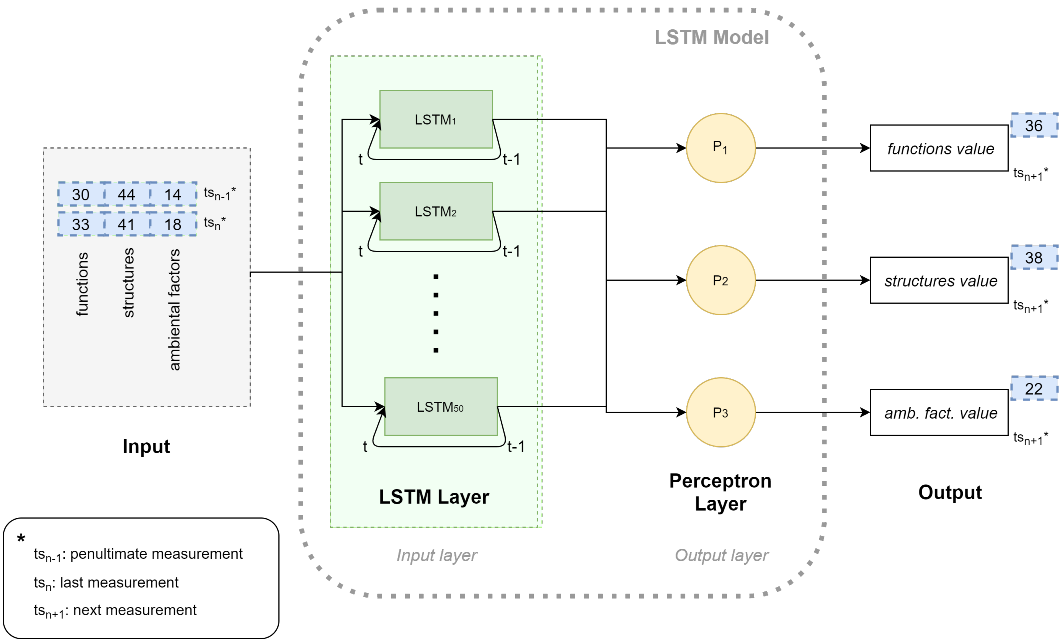


Figure 2.15: Structure of the LSTM's model for forecasting [10]

of aging people was taken as a case study. The data on the deterioration of the functional profile of aging people and their evolution was taken from the *Multidimensional Integrated Assessment Platform for elderly (MIAPe)* [83]. This platform has been developed by the author of this dissertation and has been employed by different sociosanitary institutions in Portugal for the assessment of their patients.

At the time of the study, the platform had data on around 1300 patients, of whom 647 had functional profile assessments (although not all with a long time trajectory). Even so, it served to demonstrate the feasibility of this type of proposal and open the door to further development of such proposals on the Personal Health Trajectory Framework.

2.3.2 Feature Selection

The integration of all the patient's data to be employed together in her assessments can be controversial. As well as it provides more information about the patient, it also makes it difficult to locate which are the determinant of any pathology or clinical condition. It becomes necessary to know what information to take into account at each moment [47], so as not to introduce noise both in the manual and automatic analysis of the patient's data, considering or gathering not really interesting information for their diagnosis.

As well, in many of the assessments that health professionals perform, they collect data from several variables in each assessment that it is time-consuming and infringes on their limited time, reducing their patient-facing care time [58]. Health professionals are thus forced to reduce the number of assessments that they need to perform routine care for their patients, thus reducing the sustainability and quality of care. If a clinical assessment includes redundant or irrelevant variables, then the initial set of inputs could potentially be reduced at a minimal accuracy loss, consequently easing the aforementioned time crunch situation.

To solve this problem, two types of techniques exist in the literature, which can be used together: Feature Selection techniques [61] and Machine/Deep Learning techniques [48, 46]. During this dissertation, a study has been performed on the use of these techniques on health regression problems to resolve the above-mentioned issues [11].

This study has offered a technological solution that can be used to reduce the number of items to be measured in a health assessment, allowing the diagnosis of a pathology or condition to be accomplished with almost the same precision but with fewer data. To do this, different feature selection techniques used in regression problems and available in the literature have been reviewed. In order to compare them, these techniques are applied to a real-world case study focused on the above-mentioned assessment of aging adults' functional profiles. This comparison allows us to propose new models to predict functional profiles' scores with fewer variables than the original formulas.

The first step of the study was to examine different Feature Selection techniques (and their hyperparameters configuration) in regression problems, performing a quantitative comparison and considering different aspects to evaluate the performance of each technique when applied to our case study. The specific data used were derived from 829 assessments of 716 older adults treated in 49 residential homes and medical centers in Portugal. These assessments are employed to compute five different continuous values that describe the aging adults' functional profile, making this case study a regression study.

The results obtained by a series of regression models using the selected set of features by each Feature Selection technique were also analyzed. They were analyzed in terms of correlation between inputs and outputs, providing an overview of the performance of feature selection techniques when applied to regression problems in the case study. They also provide insights into their extrapolation to other problems of this type (in other healthcare assessments as well as other application domains).

Figure 2.16 shows an example of one of the techniques evaluated and its results. This is one of the best techniques evaluated for our case study. The rest of the techniques compared and their hyperparameters configurations can be found in the article of Chapter 7 or in [11]. As well, a methodology describing how to evaluate these techniques in other cases study can be found in the article.

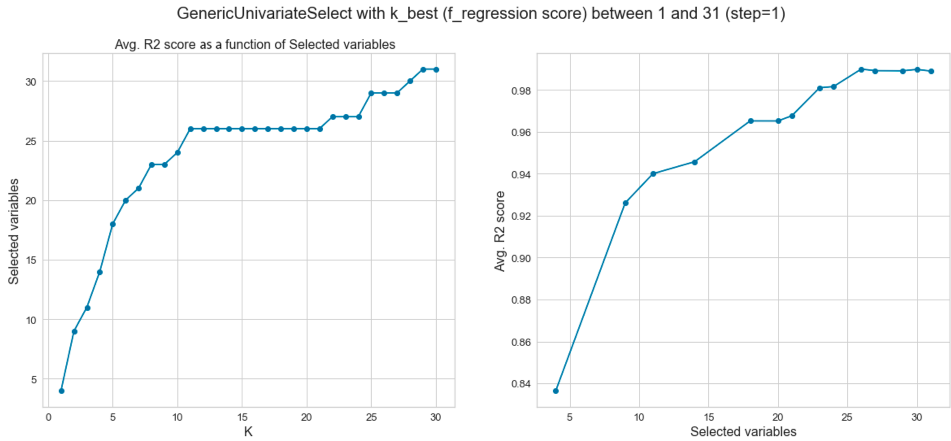


Figure 2.16: Results for the Generic Univariate Select algorithm of Feature Selection [11]

After that, a new step has been performed, developing a final proposal with the best suitable techniques and configurations from all the evaluated. The best-performing techniques were selected to create a series of models that, using a reduced set of input features, could predict the functional profile of the older adults studied with almost the same precision as the original set. In order to measure this accuracy, we provide a series of metrics on the correlation between inputs and outputs and the error introduced in the prediction models, compared to the traditional method using all the input features.

Figure 2.17 shows the final models developed. Two models have been developed using the features selected by one of the analyzed Feature Selection methods. These models predict the five functional profile scores of the patients considered: one model with higher accuracy—but using more data—, and the other with slightly less accuracy—but using a smaller amount of data.

The creation of two models illustrates the dual potential of Feature Selection techniques. Figure 2.17 shows the process followed for the creation of the two models and the use for which each model is developed. On the one hand, *Model 1* filters out a smaller number of features while offering better precision. This could be used to measure the functional profile based on the new questionnaires to be fulfilled by health professionals—now with 25 questions instead of 31. This model offers health professionals measurements of

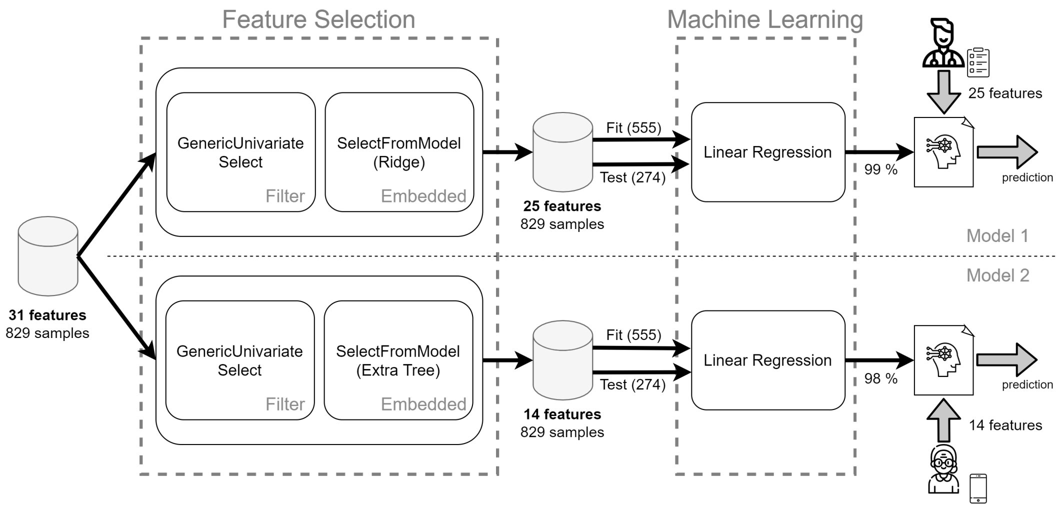


Figure 2.17: Proposal for Feature Selection on Functional Profile [11]

the different scores of the functional profile of their aging patients with almost as much precision as the original model, but with fewer questions. On the other hand, *Model 2* filters out a larger number of features (from 31 features to 14), offering slightly less precision. This model could be used by informal caregivers or by the patients themselves to perform periodic self-assessments, thus providing a more constant flow of information on their functional profile. If any irregularities were to be observed whilst applying this model, health professionals could get involved and start using *Model 1* to obtain more accurate measurements.

The results show both models achieve good correlation measured with the R^2 score. However, the error in the predictions, measured with the Mean Square Error (MSE) and Mean Absolute Error (MAE), is higher in the model with fewer features, as expected. The complete interpretation of the results can be found in the article of Chapter 7 or in [11]. In summary, it has been obtained a correlation between inputs and outputs of 0.99 according to the R^2 score and a Mean Square Error (MSE) of 0.11 when the number of features was reduced from 31 to 25; and a correlation of 0.98 and MSE of 5.73 when it was reduced to 14. These results were also published as an abstract in the article of the Appendix S [92].

2.3.3 Feature Selection Framework for Feature Selection-based Decision Support Systems

Feature Selection techniques are executed automatically on the dataset, taking as input the set of original inputs and outputs, and providing as result the subset of inputs that best describes the outputs—which may be equal to or less than the original. Therefore, from the moment the current set of inputs is provided until the moment the selected inputs are obtained, Feature Selection is executed as a black box where the user knows nothing of what is going on and cannot influence the behavior of the selection.

This can be beneficial in situations where there are no professionals in the field of application or when looking for the creation of automatic systems. However, there are other areas where the automatic application of these techniques limits their effectiveness. Especially in situations where domain experts can provide their knowledge about the difficulty of obtaining a given feature compared with its contribution to the accuracy of the results or the importance of a given feature outside the specific impact in the results.

Allowing both, the human agent and the Feature Selection techniques, to collaborate and obtain feedback from each other improves the selection results obtained. In this way, the application of Feature Selection techniques ceases to be a black box and contributes to providing solutions along the lines of Interpretable Feature Selection [113, 114] and Explainable AI [115].

In the last steps of the dissertation, proposals on Feature Selection-based Decision Support Systems (FS-DSS) have been carried out. FS-DSS approach and platform that can be easily used by non-technical users to manually perform the selection of features of different domains´ datasets, assisted by the information provided by automated Feature Selection techniques. Taking as a starting point the initial features set, the user continues selecting features—according to their domain knowledge and the automated suggestions—until they reach a subset that complies with their requirements—in terms of the number of features selected, accuracy, and precision. At that point, automated generation of Machine Learning models making predictions with selected data is provided. Figure 2.18 shows the workflow followed by the FS-DSS approach in a visual manner.

Using this approach a web platform has been developed ready to be used by health professionals to evaluate any type of health dataset. This platform has started to be evaluated on the aging adults functional profile from the previous Feature Selection research. This will allow demonstrate whether the feedback from health professionals really helps to improve the results already obtained with the automatic execution of the Feature Selection algorithms

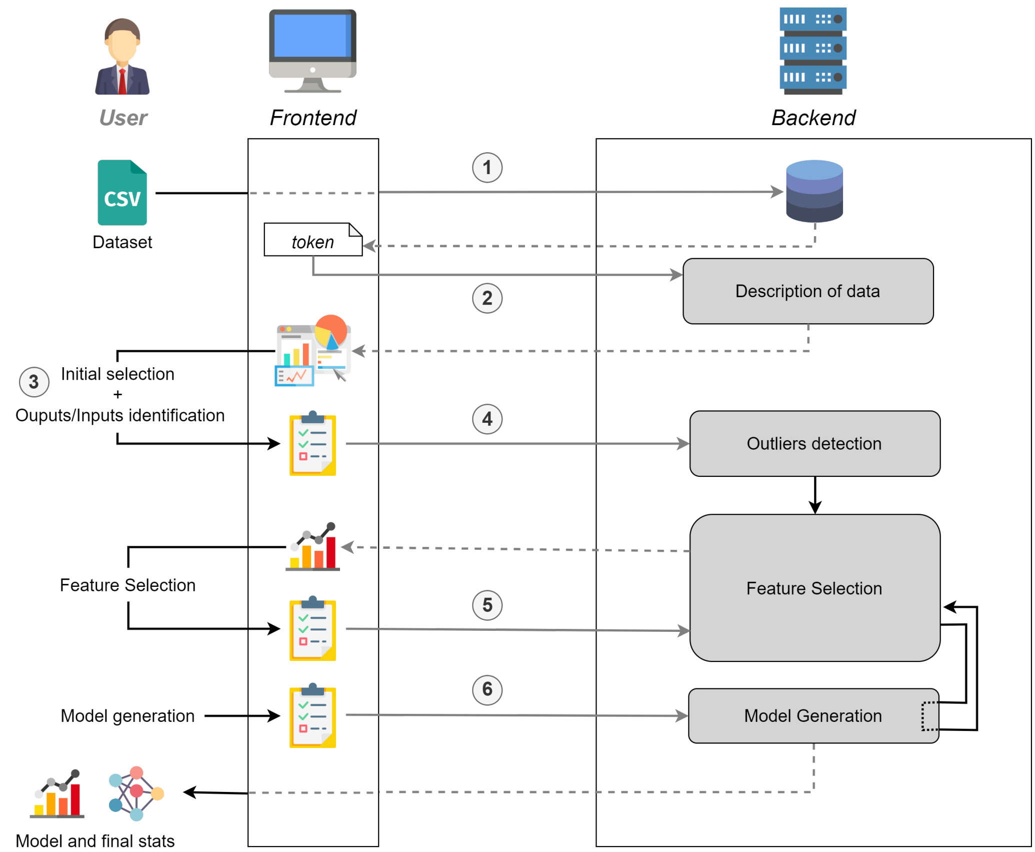


Figure 2.18: Feature Selection-based Decision Support Systems flow

in the same case study. Analyses are also being carried out on other types of assessments of aging persons. The results obtained so far have not been published at the time of writing.

2.3.4 Quantum Services in hybrid quantum-classical environments

It becomes crucial to look for alternative computations capable of analyzing situations where the amount of data to be handled is very large. Especially considering the fact that, in order to predict certain pathologies, the number of variables to be measured can still be large even after applying techniques for their selection as proposed in previous results. If it can be combined with classical computation, quantum computation has been suggested as a strong possibility in this regard.

For this purpose, the use of quantum computation as a service has been proposed, so that quantum services are developed to coexist with classical ones in hybrid quantum-classical environments. These quantum services take care of the more complex parts of the computation that classical algorithms cannot easily solve.

Figure 2.19 shows one of the examples of how to develop a quantum service today to coexist with the rest of the services in classical architectures. As can be seen, it is proposed to wrap the quantum code inside a classical service, which can be invoked by any other classical computing part. The creation of these quantum services as part of the proposal presented in [12], where quantum services for integer factorization were created.

```
from flask import Flask, request, jsonify, send_file
from flask_cors import CORS
import matplotlib.pyplot as plt

from braket.circuits import Circuit
from braket.devices import LocalSimulator

app = Flask(__name__)
CORS(app)

@app.route('/execute', methods=["get"])
def execute_quantum_task():
    bell = Circuit().h(0).cnot(control=0, target=1)
    device = LocalSimulator()
    result = device.run(bell, shots=1000).result()
    counts = result.measurement_counts

    plt.bar(counts.keys(), counts.values())
    plt.xlabel('bitstrings')
    plt.ylabel('counts')
    plt.savefig("result.png")

    return send_file("result.png", mimetype='image/png')

if __name__ == '__main__':
    app.run(host="localhost", port=33888)
```

Braket libraries for quantum computing
Classical wrapping service
Quantum algorithm

Figure 2.19: Quantum algorithm wrapped by a classical service [12]

In [94] quantum services were again created. This time to solve the Travelling Salesman Problem (TSP). In this way, a comparison was also established to show the difference between solving optimization problems such as the TSP with quantum services, versus another class of problems such as the one previously proposed with integer factorization. This discussion, and the discussion of the difference between creating quantum services with gate-based quantum computation and quantum annealing computation, was continued in [98] and in [97]. These studies served to demonstrate that both types of quantum computing can be employed in the creation of quantum services. Also, which one is better will be determined by the type of problem to be solved. Mainly, if the problem to be solved is an optimization problem, quantum annealing computing will be more optimal. If the problem is easy to model with logic gates but difficult to model as functions to be optimized, then gate-based quantum computing will be more appropriate.

In parallel, work has also been done on the direct application of these quantum services to health data. A platform has been created for the analysis of pharmacogenetic factors in the elderly using quantum computing [93]. This proposal is based on the creation of a hybrid classical-quantum system that, makes use of the advantages of quantum computing, and allows serving as technological support to health experts for the preparation of datasets and the extraction of the relationships between the different pharmacogenomic variables. In this way, the tool enables healthcare professionals to perform complex queries and facilitate the visualization of information. Thus, it is possible to predict the possible adverse effects that a given drug may have on a person's health depending on his or her pharmacological history and genetic condition. The results provided by the system help health experts to make decisions about the implementation of pharmacological treatment for a given patient with particular genomic conditions.

Other proposals have addressed the improvement of the creation of these quantum services, adapting proposals such as OpenAPI to the generation of quantum services [96]. Specifically, a tool has been proposed for the generation of quantum services given a specification and the quantum circuit code, making use of the OpenAPI specification [116]. OpenAPI allows defining and generating the code of services that can be invoked as RESTful web services. In this case, the particularity is that these services will run quantum code inside, ready to run on real quantum machines. Specifically, as proof and validation of the concept, we present the servitization of a random number generation algorithm [117], an algorithm that takes advantage of the nature of quantum mechanics to generate a truly random number.

Quantum API Gateway

One of the main results that have also been obtained within this part of the dissertation on the creation of quantum services (in order to integrate them into health systems for the analysis of health data), is to define an API Gateway designed for use in these types of hybrid quantum-classical systems: the Quantum API Gateway [13].

An API Gateway is a service composition pattern developed to allow the creation of end-user applications based on the composition of different microservices. The API Gateway serves as the system's entry point, routing requests to the appropriate microservices. It can also invoke aggregate results, transform protocols, and implement shared logic [118]. Following this approach, the proposed Quantum API Gateway is in charge of deploying the quantum service whenever a client requests it. Considering that this deployment incurs costs with every invocation, the Quantum API Gateway optimizes the deployment strategy. Whenever a quantum service is called, the Quantum API Gateway will decide at run-time which of the available quantum computers is best suited for that particular execution, thus optimizing the quantum service invocation process. Figure 2.20 exemplifies the process of calling a quantum service through the proposed Quantum API Gateway.

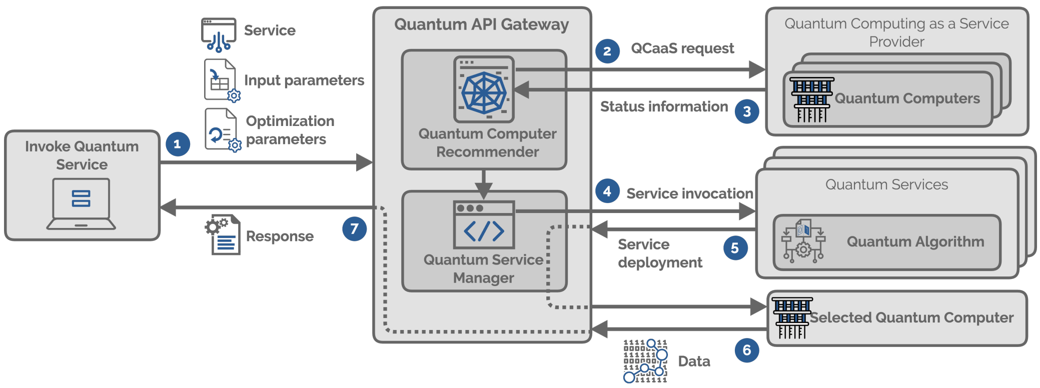


Figure 2.20: Service calling process using the Quantum API Gateway [13]

To take this decision the Quantum API Gateway will use any information available that is useful in this regard like quantum computers availability, the economic cost of the quantum hardware usage, estimated response time, etc; but also current traits of quantum computers, like qubit topology, error rate or fidelity. The availability of this information is dependent on the quantum platform supporting the Quantum API Gateway and, currently, very limited. As quantum platforms mature, more of this kind of information will be provided to users and, therefore, the capabilities of the Quantum API Gateway will be increased.

For the study carried out in [13], the implementation of the Quantum API Gateway concept has been carried out on the Amazon Braket quantum computing platform. Because of this, the algorithm for the selection of the best-suitable machine has been adapted to consider the information of the machines and of the quantum code being executed that can be obtained through this platform. Figure 2.21 shows the flow that is followed to select the machine where the quantum code is recommended to be executed when a new proposal of execution arrives at the Quantum API Gateway. As mentioned above, it can be seen that characteristics of the machines themselves are used, as well as characteristics of the code to be executed and self-imposed limitations by the user (such as the maximum cost that the execution of such quantum code can have). There may be situations in which these aspects conflict with each other and no quantum machine can be determined as optimal to carry out the execution.

Finally, it can also be seen that the Quantum API Gateway offers the possibility of going for the cheapest or fastest options, among those that have passed the rest of the filters and that is valid. For this, it is based on the user's priority, and on the calculation of the time that the Quantum API Gateway estimates that the execution of this quantum code will take in each quantum machine that is being evaluated.

Calculation of the estimated execution time for each computer is based on the characteristics of the execution, its context (namely the day of the week and the time of the start of the execution), and the actual time taken by past executions performed on that computer. In addition, another time variable is added, related to the analysis of the previous executions as a time series. This calculation is performed by a Deep Learning model that takes as input all these variables and provides as output the time required for code execution on a given machine. This time includes both the waiting time in the machine's execution queue and the time required to execute the quantum service. Specifically, a recurrent neural network of the previously mentioned LSTM type is used.

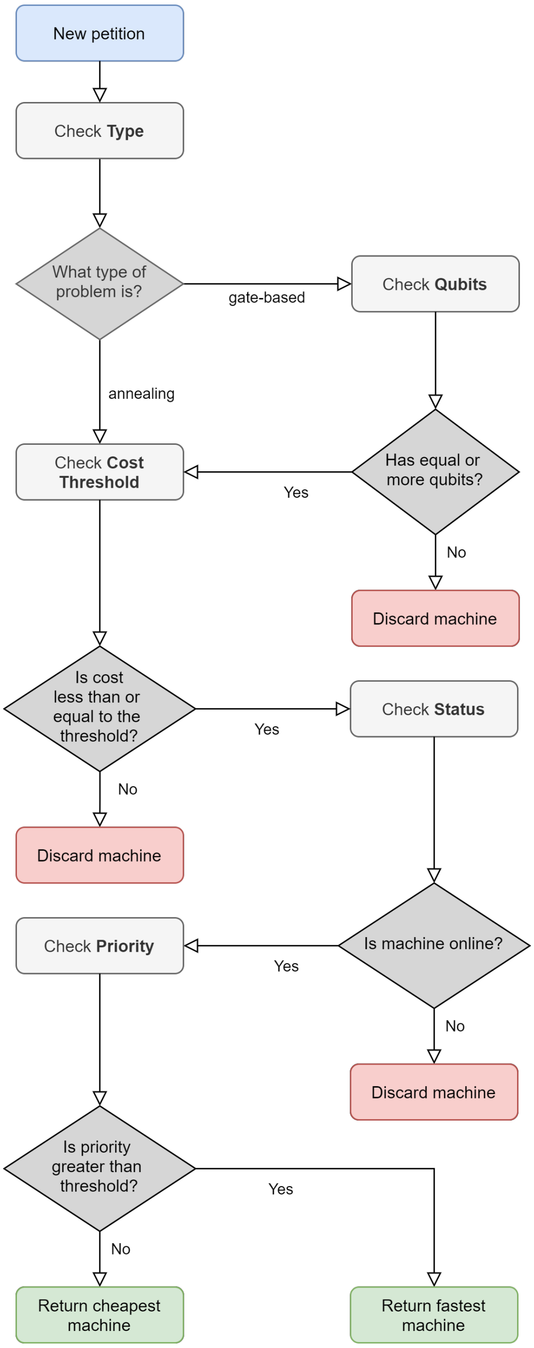


Figure 2.21: Quantum computer selection algorithm for Amazon Braket [13]

Part II

Selected publications

Chapter 3

List of publications

Contents

Once we realize that imperfect understanding is the human condition there is no shame in being wrong, only in failing to correct our mistakes

George Soros

In this chapter, the publications produced during the Ph.D. have been overviewed. First, we detail the relevant publications about the core parts composing this doctoral thesis. These compose this compendium dissertation as full papers published in high-ranking international conferences and JCR journals. They can be found in Chapters 4 to 7. After that, we detail other publications about this dissertation that serves as supporting publications. These are full and short papers in national conferences and international workshops, tool demos, and book chapters, but also other high-ranking international conferences and JCR journals that verses about topics of this doctoral thesis without being part of its core. Supporting publications can be found in Appendices A through S.

3.1 Relevant publications

During the Ph.D., the results of the main parts of the thesis have been materialized in a series of relevant publications. These publications have been focused to be published in core A or higher and class 1 or 2 conferences, according to the GGS conference rating[1], or in high-impact journals indexed in JCR. These types of venues are those defined by the CNEAI as relevant or highly relevant—for the latter, the conference must be a class-1 conference and the journal must be indexed in the first or second quartile of the JCR index.

Table 3.1 shows the list of relevant publications of this Ph.D. As can be seen, the main parts of this thesis have resulted, at the time of writing this document, in 2 highly relevant publications, both in first-quartile JCR journals (JRC Q1), and 2 relevant publications, one in a third-quartile journal (JCR Q3) and the other in a Class 2 conference. In addition to these publications, there have also been other relevant and very relevant publications in JCR journals, which are not included in this section because they are publications that do not deal with the main parts of the thesis, but their results are more transversal. These publications have been incorporated as Supporting publications to the thesis and are presented in Section 3.2.

Title	Publication date	Journal / Conference	Quality Indicator	Chapter
Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas	2021	Wireless Communications and Mobile Computing	Q3 (IF: 2.146)	4
SOWCompact: A federated process mining method for social workflows	2022	Information Sciences	Q1 (IF: 8.233)	5
Blockchains' federation for enabling actor-centered data integration	2022	IEEE International Conference on Communications	GGS-Class 2 (Core A)	6
Analyzing the Performance of Feature Selection on Regression Problems: A Case Study on Older Adults' Functional Profile	2022	IEEE Transactions on Emerging Topics in Computing	Q1 (IF: 6.595)	7

Table 3.1: Relevant Publications

The set of relevant publications presented is the one that allows this dissertation to be done following the modality of "thesis by compendium of publications". In the Doctoral Program in Information Technology of the University of Extremadura, at the moment of submitting this dissertation, it is established that those who have published the principal results of their thesis in at least three very relevant journals (JCR Q1 or Q2), two very relevant

[1] `https://scie.lcc.uma.es:8443/gii-grin-scie-rating/`

journals and one relevant journal (JCR Q3 or Q4), or two very relevant journals and one relevant or very relevant conference (GGS Class 1 or 2) will be able to do a thesis by compendium of publications. Therefore, this dissertation meets the criteria imposed by the committee because I) all the publications included in the compendium deal with the main parts of the dissertation, and II) all of them establish a set that meets the quality requirements set. The second requirement has been complied even without the need to include as relevant publications to the compendium other publications of impact not so closely linked to the core of this dissertation. These have been left as supporting publications.

3.2 Supporting publications

In addition to the main results of the thesis, there are also a number of transversal results of the dissertation, which have been published in high-impact journals and relevant conferences and are included as supporting publications to this dissertation. There are also principal parts of the dissertation that were first published as short papers or demo tools in national and international conferences, or in international workshops specialized in the topics of this dissertation. Table 3.2 shows the list of supporting publications included in this dissertation, consisting of one article in a highly relevant journal; one article in a relevant journal; two full papers, one Ph.D. Symposium paper, and one demo tool at international conferences; one full paper, one short paper, three journal-first summaries, and one demo tool at national conferences; six full papers at international workshops (some of them collocated with highly relevant GGS Class 1 conferences); and one book chapter. In total, 19 supporting publications are included that help to reaffirm the quality of this dissertation together with the relevant publications already presented.

Title	Publication date	Journal/ Conference / Workshop / Book	Publication type	Quality indicator	Appendix
Voice Assistant to Remind Pharmacologic Treatment in Elders	2020	Second International Workshop on Gerontechnology	Workshop paper		A
Automating the Interactions among IoT Devices using Neural Networks	2020	3rd International Workshop on Context-awareness for Multi-device Pervasive and Mobile Computing - Collocated with the IEEE International Conference on Pervasive Computing and Communications (Percom) (2021 GGS Class 1 Core A+)	Workshop paper		B
A Personal Health Trajectory API: Addressing Problems in Health Institution-Oriented Systems	2020	International Conference on Web Engineering	Conference paper (Ph.D. Symposium)	GGS-Class 3 (Core B-)	C
Time Series Forecasting to Predict the Evolution of the Functional Profile of the Elderly Persons	2021	Third International Workshop on Gerontechnology	Workshop paper		D
Blockchains' federation for integrating distributed health data using a patient-centered approach	2021	2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH) - Collocated with the International Conference on Software Engineering (ICSE) (2021 GGS Class 1 Core A++)	Workshop paper		E
Trials and Tribulations of Developing Hybrid Quantum-Classical Microservices Systems	2021	2nd Quantum Software Engineering and Technology Workshop - Collocated with the IEEE International Conference on Quantum Computing and Engineering (QCE21)	Workshop paper		F
Hybrid Classical-Quantum Software Services Systems: Exploration of the Rough Edges	2021	International Conference on the Quality of Information and Communications Technology (QUATIC)	Conference paper	*Work In Progress*	G
Social Events Analyzer (SEA): Un toolkit para minar Social Workflows mediante Federated Process Mining	2021	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		H
Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas (Summary)	2021	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		I
Quantum software as a service through a quantum API gateway	2021	IEEE Internet Computing	Journal article	Q2 (IF: 2.680)	J
Blockchain-Supported Health Registry: The Claim for a Personal Health Trajectory Traceability and How It Can Be Achieved	2022	Fourth International Workshop on Gerontechnology	Workshop paper		K
Social Events Analyzer (SEA): A Toolkit for Mining Social Workflows by Means of Federated Process Mining	2022	International Conference on Web Engineering	Conference paper (Demo)	GGS-Class 3 (Core B-)	L
Quantum service-oriented computing: current landscape and challenges	2022	Software Quality Journal	Journal article	Q3 (IF: 1.813)	M
Quantum software as a service through a quantum API gateway (Summary)	2022	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		N
SOWCompact: A federated process mining method for social workflows (Summary)	2022	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		O
Arquitectura Orientada a Servicios basada en Computación Cuántica para farmacogenética	2022	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		P
Generación de Servicios Cuánticos ampliando la especificación OpenAPI	2022	Jornadas de la Ciencia e Ingeniería de Servicios (JCIS)	National conference paper		Q
Quantum Service-Oriented Architectures: From Hybrid Classical Approaches to Future Stand-Alone Solutions	2022	Quantum Software Engineering	Book chapter		R
Improving the assessment of older adults using feature selection and machine learning models	2022	International Conference on Gerontechnology	Conference paper		S

Table 3.2: Supporting Publications

Chapter 4

Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas

Authors: *Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan M Murillo.*

Publication type: *Journal article.*

Journal: *Wireless Communications and Mobile Computing.*

Year of publication: *2021.*

DOI: *10.1155/2021/8874988*

2021 JCR IF (Rank): *2.146 (Q3 120/164)*

Hindawi
Wireless Communications and Mobile Computing
Volume 2021, Article ID 8874988, 15 pages
https://doi.org/10.1155/2021/8874988

Research Article

Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas

Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan M. Murillo

Department of Computing and Telematics Systems, University of Extremadura, Avda. de la Universidad S/N, 10003 Cáceres, Spain

Correspondence should be addressed to Daniel Flores-Martin; dfloresm@unex.es

Received 11 March 2020; Revised 3 July 2020; Accepted 21 February 2021; Published 12 March 2021

Academic Editor: Zhipeng Cai

The rate of world population aging is increasing. This situation directly affects all countries socially and economically, increasing their compromise and effort to improve the living conditions of this sector of society. In environments with large influxes of elderly people, such as nursing homes, the use of technology has shown promise in improving their quality of life. The use of smart devices allows people to automate everyday tasks and learn from them to predict future actions. Additionally, smartphones capture a wealth of information that allows to adapt to nearby actuators according to people's preferences and even detects anomalies in their behaviour. Current works are proposing new frameworks to detect these behaviours and act accordingly. However, these works are not focused on managing multidevice environments where sensor and smartphone data are considered to automate environments with elderly people or to learn from them. Also, most of these works require a permanent Internet connection, so the full benefit of smart devices is not completely achieved. In this work, we present an architecture that takes the data from sensors and smartphones in order to adapt the behaviour of the actuators of the environment. In addition, it uses this data to learn from the environment to predict actions or to extrapolate the actions that should be executed according to similar behaviours. The architecture is implemented through a use case based on a nursing home located in a rural area. Thanks to this work, the quality of life of the elderly is improved in a simple, affordable, and transparent way for them.

1. Introduction

The world is experiencing population aging, a trend that is both pronounced and historically unprecedented. Over the past six decades, countries had experienced only a slight increase in the share of people aged 65 years and older, from 8% to 10%. However, in the next four decades, this group is expected to rise to 22% of the total population, a jump from 800 million to 2 billion people [1].

Due to low population density and the migration of young people to richer regions, the elderly often live alone or in nursing homes where the elderly live there temporarily or continuously. These nursing homes are modernizing their facilities to provide better services and care to their residents. These improvements affect the quality of life of the elderly and the costs of nursing homes [2]. During the last few years, they are making use of technologies [3–5], to make life easier for their residents and help healthcare professionals to monitor their health and daily activities.

Over the past few years, both for aging populations and for the population at large, significant research efforts have been devoted to various aspects of health monitoring and active aging activities. One of the main objectives of the scientific community is to monitor and accurately identify the activity patterns of the elderly. Different studies have shown that the activity patterns of the elderly are a valid parameter to predict their quality of life [6]. There are approaches in this area to propose new algorithms, techniques, or systems to improve activity monitoring such as [7], focused on collecting different types of home surveillance technologies for monitoring behaviour of older people, or [8], where an architecture is developed that exploits the benefits of the Internet of Things (IoT) to capture location and other data to detect patterns of behaviour in older people in a nonintrusive way, or [7], where an IoT detection infrastructure for the city is presented that through REST and Linked Open Data application programming interfaces (APIs) collect and present data related to older people.

In this line, there are different reviews in the literature in which the different alternatives regarding the integration of Ambient Assisted Living (AAL) technology in residences are studied [9, 10]. Reviews in which network projects, middleware, sensors, communications, or actuators are proposed, although most of them with a very particular focus and for specific scenarios, mainly focused on ubiquitous sensor systems and telehealth devices.

An alternative to these residences is home care, automating and monitoring the daily activities of the elderly [11]. There are also reviews of studies and projects aimed at the elderly for the home as an alternative to nursing homes [12, 13]. But this alternative is not sufficient in rural and dispersed population environments due to infrastructure costs and the difficulty of arriving at these homes in a minimum time in case of emergency.

However, most of the current solutions provided by the research community and companies offer too closed solutions or address a very specific problem [14, 15]. Moreover, most of these solutions do not allow the integration of devices from different manufacturers or using different communication protocols [16]. Furthermore, collaboration between these types of devices remains a challenge, considering that the heterogeneity of devices and manufacturers makes this collaboration difficult. In most deployment environments, resources are limited as in rural environments or nursing homes. In this sense, the economic cost of implementation and deployment (mainly the cost of devices) of technological systems that improve monitoring is a major barrier. Moreover, due to the poor Internet connections that exist today in certain rural areas, it is necessary that the monitoring system does not depend on a permanent Internet connection to ensure its proper functioning. Therefore, it is necessary to integrate all these technologies under a common system that helps in the care and monitoring of the elderly, saving costs and giving the possibility to any nursing home to create their own smart ecosystem.

This paper presents an architecture that facilitates the integration and collaboration of IoT devices from different manufacturers. Also, this architecture makes use of machine learning (ML) techniques to improve the automation and detection of elderly people's activities in nursing homes located in rural and sparsely populated regions. In particular, this architecture can be applied to any nursing home that can conduct the monitoring of its patients through the use of the latest technologies in an affordable way and independent of the type of technology used. In addition, the architecture has been validated and promising results have been obtained in detecting people's behaviours.

The rest of the paper is structured as follows. In Motivations, the main motivations and some related literature for this paper are presented; then, in Architecture Proposal Based on IoT and ML, our proposal for rural environments is detailed, while in Use Case Description a use case is shown for a better understanding of the proposal. Next, in Results and Discussion, the obtained results and some discussions are described, and finally, in Conclusions and Future Works, the conclusions of this work are exposed.

2. Motivations

The high rate of population aging means that there are more and more elderly people in nursing homes, and as a consequence, more nursing homes are created to accommodate them. One of the main activities of these homes is to monitor the activities of the people who live there to detect behavioural routines or possible abnormalities. Current technology allows this monitoring to be carried out in a simple way through intelligent devices such as sensors and actuators [17]. These sensors and actuators are usually integrated through a central node or controller that manages the communication and the information exchange. However, in environments with limited resources such as less populated rural areas, the implementation and deployment of these IoT systems can be difficult to achieve.

The monitoring of elderly people's activities is possible thanks to the latest technologies we have today. Among these technologies, we can highlight the latest generation of sensors that can detect movement when people are walking, if a door is open or closed, if a tap leaks, if there is smoke in a room, or trigger an alarm in an emergency situation, for example. The use of sensors of this type allows nursing homes to monitor the daily activities of their inhabitants in order to detect behavioural routines or possible anomalies. There is a multitude of sensors of all types that are offered to the market by different suppliers. The choice of some sensors or others will depend on the needs that the residence has and the available budget and it will also depend on the rest of the devices to integrate into the ecosystem. Creating an intelligent ecosystem can be problematic when acquiring sensors or devices. This is due to the lack of compatibility that currently exists between devices from different manufacturers or those using different communication protocols [18]. Because of this, in environments with limited resources, alternative solutions are needed to address this problem of integration and connectivity, to provide nursing homes located in rural areas the ability to create their smart ecosystem in a simple and affordable way. In order to monitor the daily activities of elderly in nursing homes, different technology projects have been launched with the aim of establishing a comprehensive care plan in the community through the adoption of smart health and care in the area of geriatric care in nursing homes [19]. The main idea of the new smart nursing homes is the incorporation of technological devices for the monitoring of determined vital signs or specific actions of the elderly, to tackle specific aspects of health and care in these residences. On the one hand, there are solutions for personal care and integrity, such as bed-exit alarm systems [4] based on multiple sensing such as infrared, ultrasonic, and triaxial accelerometers on the route that patients pass by most often; facial recognition systems for emotion detection with smartphones to improve the quality of life of the elderly [20–22]; a smartwatch-based communication system for nursing homes [23], which improve communication between residents and caregivers, thus reducing staff response time and improving residents' safety; or an experimental smart diaper [24] as an indicator of saturation for diaper change in people with dementia living in nursing homes. On the other hand, there are rehabilitation assistance projects, such as a new electro-informatics assistive medical system [25] used for the communication with neuromotor disabled patients, which allows bidirectional communication through using an interface with a software application by using different types of sensors including switch-type sensors or eye tracking devices; a system for monitoring and rehabilitation services for elderly [26], based on mobile and wearable technologies ready to be used in residential long-term care facilities to reduce the risk of depression and social isolation; a telecare and telerehabilitation system using computer vision techniques [27]; or a software application for tablet device [3] to support social connections and reducing responsive behaviours of people with dementia while in a care setting, such as nursing homes. The use of touch screen tablets, such as an iPad, may offer the possibility of helping people in rehabilitation with dementia to remain in a care setting.

Also, other initiatives facilitate the work of caregivers and medical staff, such as devices that assist in the early intervention of diseases such as diabetes [5], dementia [28], or other diseases [29]. The authors of this paper are working on different lines to improve the life and health of the elderly; among the many works we can highlight are an extensible environment for monitoring and detecting symptoms of depression [30], different systems for food and beverage monitoring [31–33], or a voice assistant to remind the pharmacological treatment [34]. Although in this work we will only focus on the self-management architecture based on IoT and machine learning for rural areas, these approaches are interesting to be aware of the common diseases and how the caregivers can be supported.

Elderly monitoring provides valuable information to those responsible for nursing homes. Thanks to it, daily routines or possible anomalies in the behaviour of the elderly can be detected. These routines can be related to the time they get up, when they have breakfast, at what time and where they go for a walk, and even with whom they relate to most. Also, these routines can help detect abnormal behaviours such as a person spending too much time in their room, not relating to others, or performing actions outside of their routine on a regular basis [35]. All of this information is valuable to nursing homes and can be used to take action. The processing of this information must be carried out in an intelligent device through machine learning technologies. Today, there are a large number of devices that can perform this type of computing tasks, from small microcontrollers to servers specifically dedicated for such purposes. Most of the existing proposals are focused on capturing the information obtained from the cloud and processing it there [36]. In this sense, smartphones are the smart devices that are evolving the fastest and achieving more computing capacity. Thanks to this, the processing of the information that determines people's daily routines can be carried out on their own smartphone. In addition, smartphones have different types of sensors that can further enrich the information of the elderly and make their monitoring more effective. However, this processing does not allow us to obtain behaviours and anomalies from a group of people, which is essential in social environments such as nursing homes. Besides, this process should be performed in a central device that integrates the different sensors and actuators of the residence. In addition, in this paper, the authors propose to make use of these techniques in a balanced way between the central controller and the smartphones of the elderly that will allow to make better use of the available resources and avoid possible overloads.

All these proposals are a great step forward, but each of them involves the development and maintenance of a system independently. This situation complicates the development of smart ecosystems for nursing homes, as well as raising costs. For all these reasons, the main efforts should be directed towards the integration of all these proposals into a single system [37].

3. Architecture Proposal Based on IoT and ML

The proposal presented in this work is aimed at taking advantage of the benefits that the IoT offers in combination with machine learning algorithms to monitor people in order to detect pattern behaviours and to predict future actions in nursing homes with no or intermittent Internet connection. This is achieved by developing an architecture that integrates different sensors and actuators in nursing homes to improve the monitoring of elderly people and processing the gathered data by these devices. Furthermore, the correct behaviour of this architecture does not depend on the Internet connectivity as it is designed to work in rural areas with limited or no Internet connections.

Although the proposal is designed for environments with a limited Internet connection, it can be implemented in places where the connection is stable such as nursing homes located in smart cities, where there is a growing awareness of intelligent devices and they are being incorporated into people's daily lives. The proposed architecture consists of three main parts: inputs, a controller, and outputs (Figure 1). The following sections detail these three aspects of architecture.

3.1. Collecting Data: Inputs. The inputs represent those devices that can provide information about the environment, such as (1) sensors of temperature, humidity, movement or luminosity; also (2) people's smartphones that can be used to track their locations within the nursing home or frequent interactions with other devices and to provide contextual information about the person employing the different sensors they possess (accelerometer and gyroscope), such as whether they are moving, walking, and standing or any other detection that can be deduced from the smartphone's internal sensors; and (3) web services that provide additional information about the seniors' residence, such as virtual sensors to monitor weather conditions, to know the TV guide or upcoming events of interest.

In this sense, smartphones can process each person's personal information to detect patterns of behaviour through

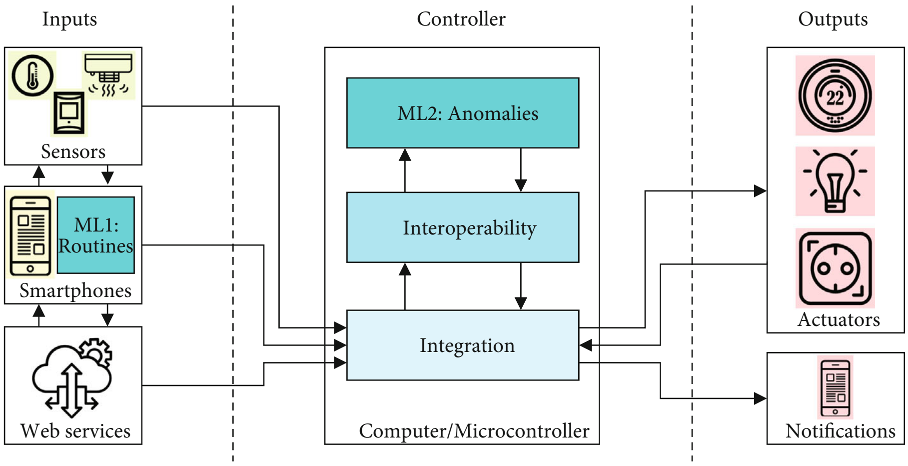


Figure 1: Architecture for the integration of sensors and actuators.

machine learning techniques. This information is related to location, interaction with other devices, data sensed by their sensors, or time invested in a room. The information is obtained through the different sensors that the smartphones have, but in addition, it can be combined with the data offered by the physical sensors placed in the residence to obtain a richer and more accurate prediction. Nowadays, mobile devices are increasingly powerful and capable. This allows increasingly expensive operations to be carried out, computationally speaking, and also at runtime, without the time delay of these processes being increased [38]. That is why the computation of the preferences of the elderly could be done directly on their mobile (ML1) devices and sent to the controller once processed, with the aim of offloading processes to the controller. In this line, many libraries offer this type of computing. TensorFlow (https://www.tensorflow.org) offers the TFLite library for running predictions on thin clients (such as Android) on models previously defined and trained with TensorFlow. Also, from the latest versions of Android (API 27), Google is working on the inclusion of an API for Neural Networks (https://developer.android.com/ndk/guides/neuralnetworks), which allows for definition, training, and prediction on the same device. Regarding this task, there are previous works [39] developed by the authors of this paper based on the use of neural networks to automate actions with IoT devices, where details of how to identify a person's behaviour and actions can be found. In that work, the detected actions depend on information from the context, such as the time, the day of the week, or the type of IoT device with which the user interact with. In addition, sensors' values and other inputs mentioned in Figure 1 are added to those input variables. Therefore, the sensors' values are considered together with the previously mentioned context variables, to determine which conditions cause an elderly to interact in one way or another with an actuator. For example, the ambient temperature captured by a temperature sensor can be decisive in how the elderly person acts with an air conditioner. The used neural network is a Multilayer Perceptron Neural Network (Figure 2), where there is an input layer of the size of the context variables that is used as an input, two intermediate layers of 45 neurons each, and a *bias* neuron in each layer, to reduce the bias of data, and an output layer of the number of actions that can be performed with the actuators. In this way, each neuron in the input layer has an associated context variable, taking its value as input to make predictions. In addition, each neuron in the output layer provides an associated action of a specific device, indicating the probability of performing that action with that device, based on the inputs specified in the input layer. The number of intermediate layers, as well as their number of neurons, is determined by adjusting the loss function and evaluating the percentage of under- and overfitting during training. This machine learning model provides the ability to discover people's pattern behaviour during the monitoring with the aim to predict actions over the actuators, but it does not provide the ability to detect behaviours that change over time (actions that stop being executed in favour of new actions). To detect these changes in elderly behaviour, it is necessary to make the neural network aware of time, to enable it to analyze not only the context variables that condition behaviour with an actuator but also the change in behaviour with the actuators (for the same or other context variable values) over time. In other words, it analyzes a time series with the changes in the way the actuators are used. For this, recurrent neural networks (RNNs) are used, which allow the neurons to be provided with memory. Specifically, Long Short-Term Memories (LSTMs) are usually used, a type of recurrent neural network that solves the short-term memory problem of classic RNNs, so long data sequences can be analyzed. An alternative to all this is to use the same neuronal network as now, creating a mechanism, like a system of weights, to evaluate positively the records of newer interactions against older ones. However, this solution is less appropriate and may give worse results than analyzing the time series of interactions with an actuator, using an LSTM. At this point, both the information processed by the smartphones and that produced by the different physical sensors are sent as output from ML1 device and as inputs to the controller, for identifying actions and social behaviours from a set of people and smart devices.

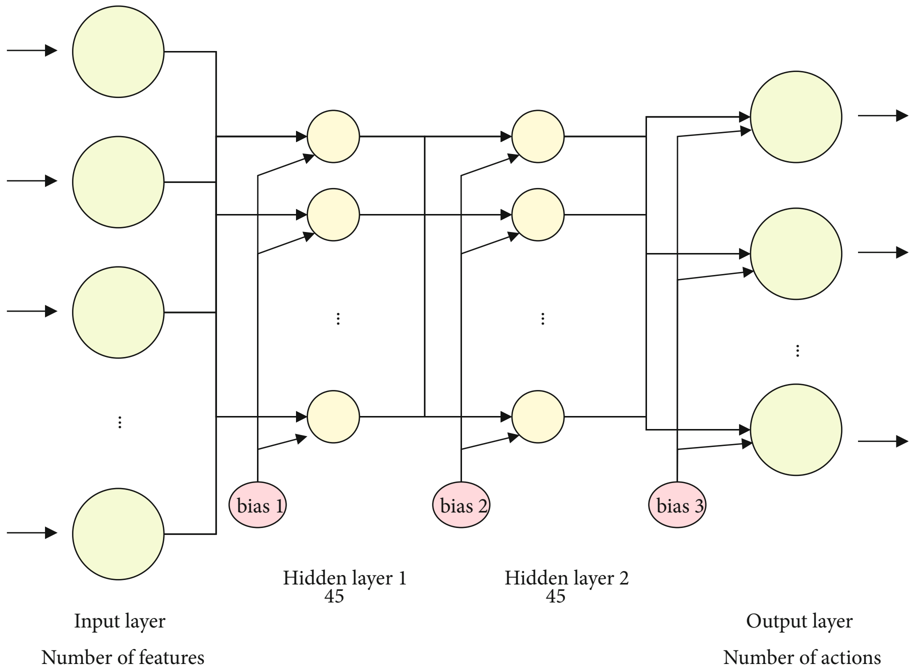


Figure 2: Neural network definition.

3.2. Processing Data: Controller. The controller, which can be from a simple Raspberry Pi to a dedicated server, processes the information coming from the different sensors and smartphones (inputs) to interpret it. The controller consists of three main components. The first component, *integration*, is responsible for ensuring proper integration among the different devices (sensors and actuators). To do this, one of the most popular assistants for the automation of smart environments is used: Home Assistant (HASS) (https://www.home-assistant.io). HASS is a system designed for the configuration and automation of many devices from different brands. It is developed in Python, which is a free and open-source software with a large community behind 216 and large support of brands (https://www.home-assistant.io/integrations) such as Amazon Alexa, Google Assistant, Ikea, Philips, Sonos, or Xiaomi. HASS allows the integration of devices (sensors, actuators, mobile phones, etc.) through a great number of different protocols like Bluetooth, BLE, WiFi, ZigBee, or MQTT, to be controlled or to make automation in a concrete environment, like a smart home, an office, or as in the case of this work, a nursing home. Also, this system allows triggering specific actions when an event occurs, such as turning on a lamp when motion is detected or sending a notification when an alarm is triggered. HASS also allows nearby devices to be detected through different mechanisms, such as those connected to the same network (NMAP), or within Bluetooth or BLE range. This is particularly interesting for finding out who is nearby, where they are by tracking devices such as smartphones, smartbands or smartwatches. The wide range of possibilities that HASS offers is an interesting option to perform the automation of the nursing home, allowing the responsible of the nursing home to purchase a wide range of smart devices. Once the devices are integrated, the *interoperability* component is responsible for ensuring the collaboration among the devices. To achieve this collaboration among smart devices, we must link elder's needs to the services that the devices offer. We define as *needs* the preferences that people have and that need to be covered in order to perform a certain task, such as for example, selecting a certain luminosity level. These needs can be manually specified by the person or be detected by another device, for example, selecting a specific luminosity level when a person is entering in a room. These needs will be covered by the *services* that the smart devices possess within the nursing home. To this end, ontologies are used to define the characteristics of the sensors, actuators, and smartphones, with the aim of creating logical relationships between them and facilitating their collaboration.

There are numerous ontologies that currently exist for healthcare in smart environments and that could be reused for the proposed architecture. In this sense, the authors of this paper developed in [40] a study of the most relevant ontologies mainly related with healthcare. Some of the ontologies included in the study are *HealthIoT*, *HOTMES*, or *FIESTA-IoT*. These ontologies can represent medical devices, provide information to perform personalized services to certain patients, represent smart environments dependent on certain conditions or parameters, or monitor different people's activities. However, none of them gathers all the information that is necessary to represent the correct communication and collaboration between inputs and outputs. A complete description of these ontologies is detailed in [40] as well as their main properties' pros and cons. The development of ontologies is usually done to solve a specific problem. It is for this reason that although the ontologies considered have classes and types of data that could solve our problem, they do not achieve it completely and do not allow us to represent the required information in the way

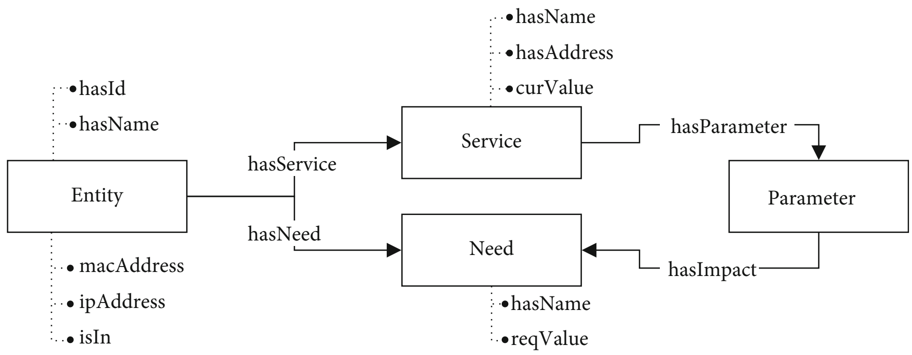


Figure 3: Proposed ontology to improve elderly monitoring in nursing homes—*Ont4SM*.

we intend to do it. This information is related to the identification of inputs and outputs, associated services such as turning on a light or triggering an alarm, parameters that indicate the operation of the services, such as the intensity of the lighting, specific preferences of people, and values of those preferences to suit the devices. For this reason, we propose an ontology to improve the interoperability among smart devices in nursing homes. The proposed ontology is defined as Ontology for Smart Monitoring (*Ont4SM*) (Figure 3). The aim of this ontology is to represent the information of smart devices belonging to different application domains and manufacturers as well as the information about people to achieve a semantic relationship.

Given the fact that both people and devices have services and needs, we use a single class (*Entity*) to represent people and the different sensors and actuators that we treat them equally. In addition, this class allows us to represent the entity's personal information so that it can be correctly identified and for the moment is not necessary to make a separation. Besides, this ontology is able to represent the services (*Service*) the entities have, as well as the needs (*Need*) that will be solved by the available services. We must bear in mind that the impact of services on needs will not always be the same and will depend on different parameters. For this reason, a class (*Parameter*) has been introduced that receives the necessary parameters to make the invocation and to adapt the service according to the characteristics of the need that it is going to solve. The following example shows how the ontology works and how the information represented in JSON format is treated. Let us suppose that a person, Bob, from the nursing home is in the living room. Through the information collected by his smartphone and contextual information, his needs (Need) are detected and interpreted by the controller and the nearby devices can adapt their services (Service) to this person as well as additional information to identify him in the nursing home (Figure 4). In this case, Bob would like a medium illumination (6/10). To solve this, the intelligent light bulb in the living room, a SmartBulb, receives the data from the person through the controller to adapt the lighting level to the detected need. In this case, the service that allows changing the lighting is invoked and receives the "illumination" parameter that acts directly on the detected need when it is solved (Figure 5). Also, the SmartBulb has an associated need to optimize energy consumption.

```
{
    "hasId":"135487",
    "hasName": "Bob",
    "macAddress":"4e:25:d5:f0:e4:4d",
    "ipAddress":"192.168.0.115",
    "isIn": "LivingRoom",
    "hasService":[],
    "hasNeed":[
        { "hasName":"Illumination",
          "reqValue": "6"

        }
    ]
}
```

Figure 4: Entity Bob.

```
{
    "hasId":"21547",
    "hasName": "SmartBulb",
    "macAddress":"db:93:09:a5:5c:69",
    "ipAddress":"192.168.0.140",
    "isIn": "LivingRoom",
    "hasService":[
        {
            "hasName":"Illumination",
            "hasAddress":"http://192.168.0.140/service?
                    illumination=value",
            "curValue":"0",
            "hasParameter": ["illumination"] }
    ],
    "hasNeed":[ {
            "hasName":"Consumption",
            "reqValue": "2"
        }
    ]
}
```

Figure 5: Entity SmartBulb.

If there is a nearby entity that can perform this optimization, for example, lifting a blind for natural light entering so that the bulb can be turned off temporarily, the process would be repeated so that this need would be resolved by the service of the nearby smart blind.

The processing of the ontology goes through several phases from the entities which are detected in the nursing home, until the information is processed to improve the elderly monitoring. This is a brief description of the ontology, so all the details about it and its processing is available in [40]. The last component of the controller, *ML2Anomalies*, is responsible for processing the information collected to detect possible anomalies in people's behaviour. In addition, this component allows us to discover social behaviour that can be identified within the nursing home, such us the frequency with the people interact between them, what are the most interesting topics they talk about or if they develop certain task together, such as play a game or go for a walk. This can be done by using machine learning techniques. Thanks to these algorithms it is possible to process the information gathered from the inputs and to make a decision that allows the adaptation of the actuators or to predict future actions in the environment. To do this, unsupervised algorithms are used for anomaly detections. Anomaly detection, in data mining, is the process of detecting, for a large dataset, observations from this dataset that differ significantly from the values taken by most other observations. Therefore, it is used in tasks such as fraud detection [41]. Due to the unsupervised algorithms work with unlabeled data, the previous data that was used as input (sensors) and output (actuators) is used as input for the anomaly detection algorithm. This allows certain areas to be identified where the elderly is interacting normally with the actuators, according to the input data from the sensors, for example. When unusually operating with the actuators according to the inputs, this interaction produces data that is outside any of the zones where most of the data is, assuming that the elderly are performing an action that differs from their usual behaviour. Also, it is important to indicate that, although the information of which elderly performs a certain interaction with the sensors/actuators is saved and it is considered as part of the model entries, the information will always be processed globally for the whole residence, so the models generated will be at the residence level (one model to automate actions and another to detect anomalies) and not models for each elderly. In this way, it will be possible to extrapolate the models from a residence to a similar residence, as will be seen in Results and Discussion.

3.3. Taking Actions: Outputs. Finally, the outputs represent the actuators that are in charge of triggering different actions depending on the information that has been previously processed. These actions will vary depending on the type of actuator, such as setting a certain illumination, regulating the temperature of a room, tuning to a specific channel on the television, and turning on/off a device connected to the electrical current. Additionally, push notifications, or any other type of notifications, could be sent to caregivers in case of emergency. One of the main advantages that this architecture has is that it does not require an Internet connection. Once the architecture is implemented, the sensors and actuators are connected through different communication protocols to the controller, which is in charge of performing all the information processing locally. The integration of these three parts of the architecture, inputs, a controller, and outputs, contributes to improving the elderly monitoring in a transparent way for them mainly in environments with limited or no Internet connection such as rural areas or small villages, isolated from the big cities.

4. Use Case Description

The proposed use case is based on a nursing home located in a rural area with limited resources. In this residence, it has been proposed to monitor the daily activity of the elderly living in the second floor to check what activities they do or when and even to detect strange behaviours. To do this, the nursing home's caregivers want to use the latest technologies that allow data to be collected and processed in the most efficient and easy way. Due to limited resources, such as Internet connectivity or a minimal budget, it required a solution that they can perform simply and affordably.

For the proposed use case, it has been decided to use three different communication protocols (WiFi, ZigBee, and Bluetooth) to take advantage of the benefits of each of them and to cover a wider range of different devices' specification. In addition, the use of different technologies serves as a complement to evaluate the integration, collaboration, and interoperability among different sensors and actuators. The selected sensors and actuators are shown in Table 1, as well as the different smartphones that the elderly living in the residence have.

In Figure 6, the floor plan of the second floor of the nursing home on which the current case study is conducted is shown. In this floor, there are four rooms for people, a living room, and the central corridor automated with sensors (*green*) and actuators (*red*). Each room is provided with a sensor to control when the windows are opened and closed, as well as a bulb to change the luminosity or color, and a socket to turn on/off any electronic device connected to it, for example, a TV or a radio. Besides, sensors to control the opening of windows and smoke detection, temperature, and movement sensors have also been installed in each living room. In addition, the living room has sockets that allow elderly to activate or deactivate any device connected to it, a smart button that allows elderly to interact with the light bulbs or other smart devices, a bulb that can change its intensity or color apart from being turned on/off, and a thermostat that allows to regulate the temperature of the room. Different devices have also been installed in the corridor to monitor the activities of the elderly. In the corridor, there are a movement sensor, a smoke detector, and a general alarm that allows for notification of possible incidents. On this second floor, four elderly people (*yellow*) are currently living, who move freely between the rooms and the living room to perform personal, social, or leisure tasks. Each person has its personal smartphone that collects information about their position, who is near them and even the most used applications, to recognize behaviour patterns in their daily routines. These smartphones are constantly gathering data from the different sensors they have with the aim to detect behaviour pattern about

Table 1: Selected controller, sensors, actuators, and smartphones for the use case.

Device	Supported protocol(s)	Description
	Controller	
(i) Raspberry Pi 3 Model B+	WiFi/Bluetooth/ZigBee	The controller to manage the environment
	Sensors	
(i) Motion sensor Xiaomi	ZigBee	To detect movement
(ii) Temperature/Humidity Xiaomi	Bluetooth	To control the temperature and humidity
(iii) Doors/Windows closed Xiaomi	ZigBee	To detect when a door or window is opened
(iv) CR Smart Home Smoke Xiaomi	ZigBee	To detect smoke/fire
	Actuators	
(i) Xiaomi Yeelight Color V2	WiFi	Bulbs to illuminate rooms/corridors
(ii) Smart Plug Zoozee	WiFi	Plugs to control electrical devices
(iii) Google Nest	WiFi	Thermostat to control the temperature
(iv) Smart Switch Xiaomi	ZigBee	Button to trigger different actions
(v) Xiaomi Aqara Gateway	WiFi/Bluetooth	Alarm to trigger notify emergencies
	Smartphones	
(i) Xiaomi Mi 9	WiFi/Bluetooth	Elder's daily data
(ii) Huawei Mate 20	WiFi/Bluetooth	Elder's daily data
(iii) Moto Z	WiFi/Bluetooth	Elder's daily data
(iv) Honor 9	WiFi/Bluetooth	Elder's daily data

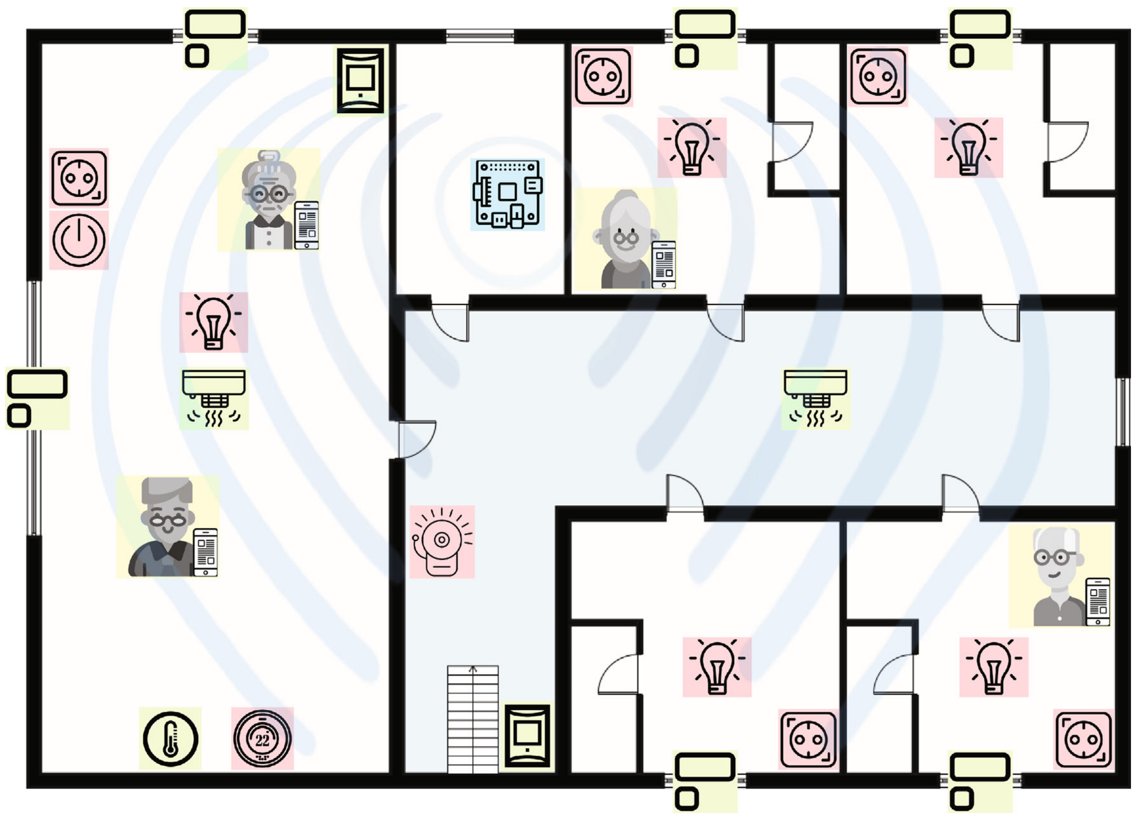


Figure 6: Nursing home floor plan (2nd floor) use case.

their owners by using the machine learning techniques previously explained. Also, in this second floor, a controller is located, a Raspberry Pi (*blue*), that receives and sends information from sensors, actuators, and elderly smartphones via WiFi, Bluetooth, and ZigBee, depending on the type of device. All these devices have been integrated through HASS to perform the appropriate automations as well as to adapt their behaviour to the environment. The information collected in this environment is processed through unsupervised algorithms previously detailed in the controller to detect anomalies in elderly behaviours.

Thanks to the structure of the proposed architecture, as well as the technologies it uses for the integration of devices and information processing, the data collected in this use case are potentially usable for the detection of behaviour patterns and anomalies in residences with similar characteristics (number of people, arrangement of sensors and actuators, size of the building, location, etc.).

5. Results and Discussion

The need for mechanisms to facilitate the monitoring of older people is increasingly real. The increase in the average age of the population poses new challenges to societies and healthcare systems. Nonetheless, the emergence of the area of IoT research, wireless communications, and mobile computing is raising hopes for automated assisted environments. These environments combine the advances of sensor networks with those of run-time monitoring systems, to create intelligent nursing homes capable of monitoring the elderly. However, although various AAL systems have been proposed in the last years, the goal of realizing an effective support system for elderly is still far from reach. That is why, in this paper, we have presented a project aiming to reengineer a set of everyday life objects, equipping the nursing home with different types of sensors and actuators, thus monitoring the condition of older people in their nursing homes and providing security while preserving the autonomy and independence of the persons, in an environment with limited resources such as rural areas. This solution is based on an architecture capable of managing different types of devices, such as sensors, actuators, and smartphones with an algorithm to detect pattern and anomalies in elderly behaviour.

The developed algorithm to detect pattern behaviours has shown promising results. The following results are an extract of the main work developed by the authors of this work [39] where the neural network developed and evaluated in different scenarios for the detection of behavioural patterns in different scenarios of people is presented.

In this case, these results are related to the (*ML1: Routines*) component of the proposed architecture. The results shown correspond to the behaviour of an elder in the nursing home who performs different activities from Monday to Friday, on Saturday he/she goes for a walk, and on Sunday he/she goes to his/her children's house. The validation lasted three weeks. The two first weeks were used for training the model with information about the different actions that the users performed with the present devices for this scenario. And the last week was used for the testing phase in order to get prediction and evaluate them. Some predictions were also made during the two weeks of training, to check how much data were needed for the system to start learning new behaviours and how the predictions improved with new records. However, this depended a lot on how frequent the behaviour is. First, regarding the responsiveness, it is interesting to indicate that on average 11.05 seconds are required to refit the neural network with the inputs of each user every day and 1.35 milliseconds on average are required to make a prediction. As can be seen, the responsiveness is very good for almost any IoT application. Other similar proposals [42] are getting prediction times of 896.1 milliseconds (when the number of devices is small) and 1.21 seconds (when the number of devices is higher). Training times are not included in these proposals. Second, regarding the accuracy, the results obtained for the scenario can be seen in Table 2. In this table, the number of predictions, the correct and the incorrect ones, is detailed.

Table 2: Table of predictions.

Predictions	Correct	Failed	Accuracy
245	212	33	0.86

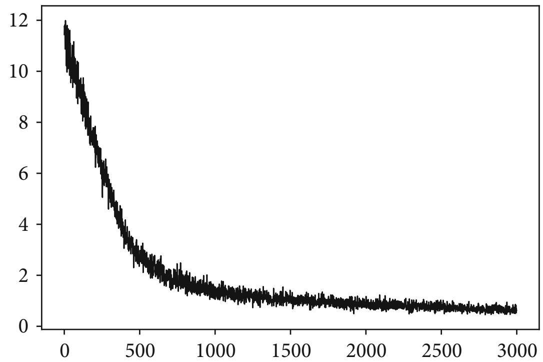


Figure 7: Loss function for the validation model.

By analyzing the joint results for that scenario, we have to notice that 33 predictions were not correct. According to this, we detected that 29 were produced by trying to predict actions that do not have a specific behaviour pattern, since there were records of different actions for the same device in the same context and for the same user. For example, imagine a person who sets a different television channel every day when arriving at the nursing home. If the system tries to predict which channel the person will choose, the probability of getting a correct prediction is low. For the other 4 incorrect predictions, the model was not able to learn the action. Therefore, it can be said that only 4 out of the 245 predictions were not correct.

In addition to analyzing the results offered by the model in terms of accuracy, it is important to analyze other functions measuring the quality of the developed model. For this purpose, the loss function has been used. The loss function for the model discussed in this section is shown in Figure 7. It can be seen how the function tends to the value zero (target value in this function), which allows us to know if the value of the learning rate or the value of the batch size is appropriate. To do this, the evolution of the loss function through the epochs is compared with the ideal evolution of the loss function [43]. Thanks to this analysis, it can be determined that the learning rate is good, although it could still be reduced a little. The noise that can be observed in the loss could be reduced by decreasing the batch size a little but is not significant.

Table 3: Table of measures over probabilities.

Measure	Correct predictions	Failed predictions
Min. value	0.3266	0.3266
Max. value	0.9923	0.9667
Average	0.7825	0.5898
Typical deviation	0.1800	0.1850

In addition, we also evaluated the probability of success for every prediction in order to identify a *threshold* that allows us to know when a predicted action should be performed or not. In Table 3 can be appreciated the average, the maximum, and the minimum value and standard deviation for the probability of the correct and failed actions.

Finally, to determine the *threshold*, a *univariate* distribution has been created with the value of the probability of success of the correct (Figure 8(a)) and failed (Figure 8(b)) predictions. Thanks to these data and reducing the number of false positives even if the accuracy is reduced, it can be determined that the best *threshold* is over 0.4 and 0.5. Besides, in Table 4, it can be observed that a *threshold* of 0.44 is better, because a lower *threshold* includes more false positives.

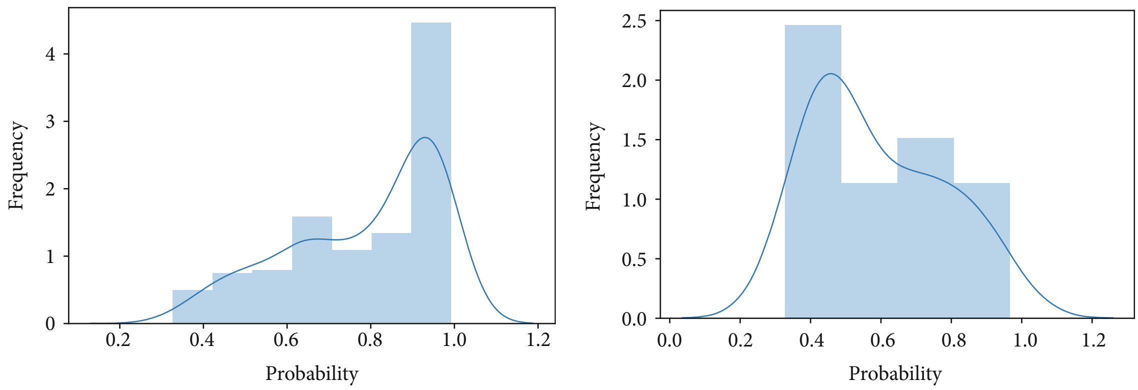
With the obtained results, it can be stated that the algorithm has been able to correctly predict 86% of the interactions, failing only in 1% of the predictions or when the performed actions do not follow a pattern.

Regarding the machine learning algorithm development, another way to implement them to detect pattern behaviours and anomalies can be by developing a single model using the neural network for both functions. Each time an elder performs an action manually, he/she employs the neural network to check the probability of execution of that action, according to the model trained with previous records and the context (inputs). By assigning a minimum probability threshold, if the action being executed by the elder does not exceed the threshold in the prediction model, it is considered an anomaly. This is because the elder is performing an action that has very little probability of being performed according to his/her usual behaviour. Also, it is necessary to verify that there are actions that the elder could perform at that moment that exceed the threshold. If not, the reason why the performed action did not exceed the probability threshold could be that the model is not sufficiently trained for that situation and not because of an anomaly. However, this method is more susceptible to errors, since there are already dedicated algorithms to do this. It could be useful in case we wanted to reduce to the maximum the amount of computation and complexity of the controller, using a machine learning model for everything. This may be a way to reduce the energy footprint on the controller.

Although the selected use case is based on a nursing home with specific characteristics, the proposed architecture can be implemented in another nursing home. This is especially beneficial. This work is part of a project on gerontechnology, in which one of the tasks is to define an architecture that can be used in all residences in the regions of Extremadura (Spain) and Alentejo (Portugal). This architecture and implementation allows to reduce the costs of the residences and be more efficient in caring for their residents. The benefits of the proposed architecture should be considered when implementing this as well as the requirements of the destination nursing home. These benefits include the wide variety of sensors and actuators that can be integrated, regardless of the manufacturer and technology used. More and more devices are compatible with systems like HASS, which allow users to create their own intelligent environment without having to rely on third-party applications or hardware to operate and communicate with each other. This allows the application to be used in rural environments, even if it has no Internet connection or is limited, because all information processing is done locally at the controller. To implement the architecture in any other scenario, it would be necessary to study the available resources and the available budget. Furthermore, it would be necessary to study the requirements, mainly the type of sensors or actuators to be used, depending on the type of monitoring and the performance to be achieved. For example, monitoring the movement of people or if the lights remain on for a long time. In addition, it must be decided what type of controller will be suitable for managing the environment, from a microcontroller to a dedicated server with more power and resources. This decision will vary depending on the size of the environment and the number of devices being managed. Once the sensors, actuators, and the controller have been identified, they must be integrated into the HASS installed in the controller so that the information from the sensors, actuators, and smartphones can be processed by the machine learning algorithm to detect behaviour patterns or predict certain actions. If the new scenario in which the architecture is to be implemented has the same number and type of sensors and actuators as any other previously known scenario, the machine learning models can be exported from the known scenario to the new one.

Otherwise, if some of the inputs or outputs were different, it would be necessary to modify the inputs and outputs of the models, having to generate new models and train them from scratch. From this moment, it is possible to start with data collection and environment automation to perform the necessary tasks.

The system developed promises to be of great help to older people, especially in environments with reduced or no Internet connection such as rural areas. As mentioned above, the proposed architecture can also be applied in residences located in settings with good Internet connections. These environments can even enhance the characteristics of the proposal, allowing tasks to be performed remotely, such as controller management, using cloud services for more complex data processing or monitoring the status of people in the residence from other locations. In the case of remote management, HASS makes it easy to do so through the *Nabu Casa* (https://www.nabucasa.com) service, which allows access to the control panel from anywhere through the Internet browser. In this way, the HASS can be managed and the information of the sensors installed in the nursing home can be evaluated. For data processing in remote servers, the great versatility that the Raspberry Pi offers would allow one to easily cloudify these services, using Amazon Web Services



(a)

(b)

Figure 8: Univariate distribution of probabilities: (a) for correct predictions; (b) for failed predictions.

Table 4: Table of measures over threshold.

Threshold	False neg.	False pos.	Correct	% success
0.40	5	30	210	0.8571
0.42	10	26	209	0.8530
0.44	11	23	211	0.8612
0.46	13	22	210	0.8571
0.48	17	21	207	0.8449
0.50	21	19	205	0.8367

(AWS) (https://aws.amazon.com) or Microsoft Azure (https://azure.microsoft.com), to send the data and to be able to recover the results once processed. This feature could be added in the future to expand the possibilities of the architecture and support new features. Although the potential benefits of the proposed architecture have already been shown, further work is needed to overcome current limitations. Among these limitations is the amount of data required for the machine learning model to be able to act correctly. In this sense, machine learning models are more accurate when they have a large amount of data, so when used in small environments with few interactions with actuators, data collection can take a long time until the model begins to generate more reliable predictions. For the studied scenario, Figure 9 shows a line chart with the evolution of the accuracy of predictions with respect to the amount of data that has been collected. This chart shows the evolution of the accuracy in the 3 weeks that the validation lasted. However, only data for 15 days are shown, because the user did not use the system every day of these 3 weeks. When there were no interactions, the model was not retrained. These days are not represented in the chart in order to improve its readability. In this chart, it can be seen how, as the size of the datasets grows, the gap of the accuracy between the training and testing datasets (the overfitting) is reduced. It is important to mention that the training is done with data from real users. Then, the accuracy evolution depends on how they use the system. If a user always uses the system with a strongly determined behaviour, the amount of data needed to obtain good predictions will be low. If not, more data are needed and the algorithm will not be able to offer high accuracy predictions in all cases.

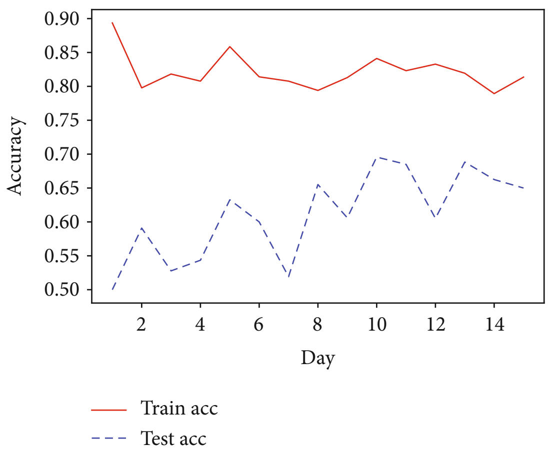


Figure 9: Evolution of accuracy along validation period.

During the training period, the model is trained with the actions performed in the different devices. Therefore, if the user has a random behaviour with any of them, the accuracy goes down, even if the probability of success of the model for the rest of the devices is high. To finish analyzing this figure, it is important to note that the accuracy values for the last measurements are not identical to those in Table 2. This is because the accuracy shown in Table 2 is obtained based on the number of actions that is automated by the user with the last trained model and the number of these actions that the user accepts or corrects immediately. The accuracy shown in this graph is the one obtained at the moment of training the model and testing it. Figure 10 shows, for the same period, the time needed for training (using CPU) and the space required to store the dataset. The training time is divided into two phases that are part of the training phase: *data cleansing* and *fit network*. In this way, the amount of training time dedicated to each of these tasks is shown. From the chart, it is possible to see how adding more data to the dataset does not considerably affect the time needed to train the model. This is because the amount of data that is collected in this timeframe is small, as can be seen in the *size dataset* (on the order of kilobytes). The number of inputs that the neural network model has for this scenario is small. If the

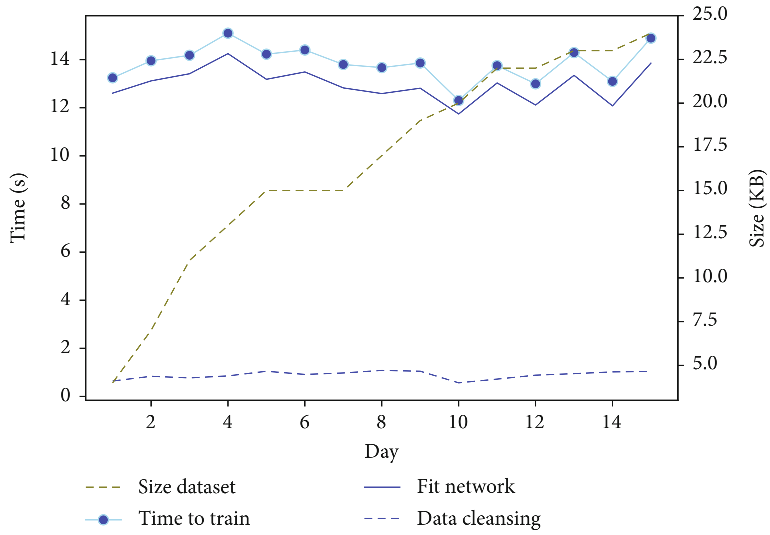


Figure 10: Evolution of time and space needed for training along validation period.

number of inputs in the model grows, the increment of the space occupied by the dataset with respect to the timeframe will be greater.

Another current limitation is that the information collected from smartphones is limited to space and time variables. To obtain other types of information, it would be necessary to install a mobile application that provides more detailed information.

In addition to these limitations, a procedure to evaluate the architecture has been performed using the ATAM (Architecture Tradeoff Analysis Method) methodology [44]. ATAM allows the evaluation of software architectures through nine steps grouped into four phases (presentation, research and analysis, testing, and reporting) to mitigate risks related to quality, performance, availability, security, and modifiability. One of the benefits of ATAM is that it can be used during different parts of the architecture's life cycle, either at the beginning when the architecture is being designed, throughout its life cycle, when the architecture is defined but barely developed, and even for a fully defined architecture. In this sense, the evaluation of the architecture proposed in this paper is made in a preliminary way to know the most important risks that it may contain.

(i) In terms of the quality of the architecture, the proposal advocates offering nursing homes the latest technologies for the domotization of smart environments. Among these technologies, the use of machine learning algorithms (TensorFlow) for data processing, or Home Assistant for the integration of intelligent devices, stand out. Also, these technologies have wide support from the scientific community, which allows the quick identification and solution of problems and a more than acceptable capacity of expansion. The risks associated with the quality of the architecture reside in the degradation of the physical devices over time and with the conditions of the environment, where interference with other devices or the physical layout of the walls of the residence could affect the architecture behaviour

(ii) The performance of the architecture depends on the type of devices selected for monitoring the nursing home. The architecture is designed to accept any type of device and taking into account that this implies a cost for the nursing home's managers. Moreover, since the controller is the main device, it can be more or less powerful depending on which ones are chosen. In the example proposed, we have chosen to use a low consumption microcomputer (Raspberry Pi) whose characteristics are sufficient for a small-medium size environment. However, the capacity of this device can be reduced depending on the number of devices that are integrated and the size of the nursing home. This is why this device can be replaced by higher performance elements such as a dedicated server to carry out all the required processing

(iii) In an intelligent environment, the availability is a key property. However, this feature often depends on the network infrastructure. In this case, the nursing home does not have to offer an Internet connection, but it must have at least one gateway (a router) enabling a local network with intelligent devices. Furthermore, although only one controller has been proposed to be installed, this could be replicated in another area of the nursing home to make the architecture fault-tolerant in case errors are triggered by a controller. For environments where there is an Internet connection and where the characteristics of the architecture can be extended, again there must be a backup system that allows the output to the Internet in case of an error

(iv) Also, the security supposes a fundamental aspect in software architecture. On the one hand, the architecture contemplates that the devices can be connected through secure P2P protocols against the controller, using WiFi, Bluetooth, or ZigBee technologies. This means that once configured, the devices only communicate with the controller to send and receive data. On the other hand, the privacy of people's data is a crucial aspect. This is since sensitive personal data is handled. Therefore, the authors of this paper are firmly committed to data privacy and have been working for some time to guarantee this privacy. In this sense, the authors of this paper are working on a framework that allows people to decide what information to share and with whom [45]. This allows residents to decide what information will be shared from their mobile devices with the rest of the devices and the controller. Therefore, data privacy is guaranteed and only the data that people want is shared. Another important point is that taking into account that no Internet connection is required and that the processing is done locally, the data does not travel to remote servers, thus reducing the chances of eavesdropping by third parties

(v) Finally, the characteristics of the architecture allow it to be easily adapted or modified, improving the system scalability. Both the integration of new devices and the configuration of existing ones are done intuitively from the controller by using the GUI provided by Home Assistant. However, it must be taken into account that the evolution of smart devices advances at great speed and that the communication protocols are constantly updated. This means that the controller must have its libraries updated to ensure the greatest possible compatibility with new devices. Also, Home Assistant is such a versatile software that any type of script can be incorporated to modify the behaviour of the controller or to add new functionalities easily. As for data processing, the machine learning algorithms used to allow them to be retrained with new data to detect new patterns or anomalies in patients easily. The previous paragraphs largely summarize the most important risks detected through ATAM. Although this is a preliminary report, the authors of this work plan to continue with this methodology during the architecture's life cycle to detect new risks that may arise to offer a solution with the highest possible quality

6. Conclusions and Future Works

This paper deals with the problem of automating environments to make everyday tasks easier for the elderly, through the use of smart IoT devices and machine learning techniques. To this end, an architecture has been proposed that, through a controller, allows data to be collected from multiple types of sensors and smartphones, to modify the behaviour of the available actuators under people's preferences. To favour multidevice environments and give users the freedom to use different types of sensors and actuators, the architecture is capable of working with WiFi, ZigBee, and Bluetooth (among others) communication protocols. Also, a neural network model has been developed that, from the data collected, allows the controller to be able to learn about the habits and routines of older people, predict future behaviour, and detect anomalies. This information analysis is also valuable for informing family members or health experts of the habits or routines that older people normally follow, reporting abnormalities or notifying in emergencies.

To validate the proposed architecture, the implementation has been done in a daily environment where many elderly people live: a nursing home. Thanks to the conducted automation, it is possible to detect when one or several people enter a room and turn on the TV, to turn off the lights when they leave, or to turn on the heating at the time they normally go to the living room. These interactions are also valuable in improving the model more and more. When data from a longer period becomes available, the use of the mentioned LSTM networks will be evaluated if it is necessary to allow the system to learn to identify changes in the way elderly interacts with the actuators. As future work, the implementation for the detection of anomalies (*ML: Anomalies*) by means of unsupervised algorithms will be performed. Besides, the conducted machine learning model will be extrapolated to an environment with similar characteristics to evaluate its operation and to be able to adjust those parameters that are necessary.

Thanks to this proposal, better monitoring of elderly people in nursing homes is achieved through the use of all kinds of intelligent devices, thus improving their quality of life and the effectiveness of their caregivers. Also, the flexibility and scalability that the presented architecture offers allow nursing homes to implement the system with a wide range of devices and without the need for an Internet connection.

Data Availability

The data used were obtained from tests conducted with real users. They are available upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was supported by 4IE+ project (0499_4IE_PLUS_4_E) funded by the Interreg V-A España-Portugal (POCTEP) 2014-2020 program, by the Spanish Ministry of Science, Innovation and Universities (RTI2018-094591-B-I00 project and FPU17/02251 and FPU19/03965 grants), by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

[1] D. E. Bloom, S. Chatterji, P. Kowal et al., "Macroeconomic implications of population ageing and selected policy responses," *The Lancet*, vol. 385, no. 9968, pp. 649–657, 2015.

[2] D. J. Hamann and K. C. Bezboruah, "Outcomes of health information technology utilization in nursing homes: do implementation processes matter?," *Health Informatics Journal*, vol. 26, no. 3, pp. 2249–2264, 2020.

[3] L. Hung, A. Berndt, C. Wallsworth et al., "Use of touch screen tablets to support social connections and reduce responsive behaviours among people with dementia in care settings: a scoping review protocol," *BMJ open*, vol. 9, no. 11, p. e031653, 2019.

[4] C. T. Wu and C. H. Chen, "Design and implementation of bed-exit alarm system for preventing elderly falling," in *Advances in Intelligent Systems and Computing*, vol. 957, pp. 280–290, Springer Verlag, 2020.

[5] R. Mathews, C. O'Malley, J. M. Hall, L. Macaden, and S. Mac Rury, "Diabetes, care homes, and the influence of technology on practice and care delivery in care homes: systematic review and qualitative synthesis," *JMIR diabetes*, vol. 4, no. 2, article e11526, 2019.

[6] M. Á. Antón, J. Ordieres-Meré, U. Saralegui, and S. Sun, "Non-invasive ambient intelligence in real life: dealing with noisy patterns to help older people," *Sensors*, vol. 19, no. 14, p. 3113, 2019.

[7] R. Mulero, A. Almeida, G. Azkune et al., "Anaal system based on IoT technologies and linked open data for elderly monitoring in smart cities," in *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (Spli Tech)*, pp. 1–6, Split, 2017.

[8] M. Uddin, W. Khaksar, and J. Torresen, "Ambient sensors for elderly care and independent living: a survey," *Sensors*, vol. 18, no. 7, p. 2027, 2018.

[9] J. Doyle, A. Kealy, J. Loane et al., "An integrated home-based self-management system to support the wellbeing of older adults," *Journal of Ambient Intelligence and Smart Environments*, vol. 6, no. 4, pp. 359–383, 2014.

[10] A. Patel and J. Shah, "Sensor-based activity recognition in the context of ambient assisted living systems: a review," *Journal of Ambient Intelligence and Smart Environments*, vol. 11, no. 4, pp. 301–322, 2019.

[11] B. B. Bastaki, T. Bosakowski, and E. Benkhelifa, "Intelligent assisted living framework for monitoring elders," in *Proceedings of IEEE/ACS International Conference on Computer Systems and Applications, AICCSA*, vol. 2017, pp. 495–500, Hammamet, Tunisia, 2018.

[12] R. Al-Shaqi, M. Mourshed, and Y. Rezgui, "Progress in ambient assisted systems for independent living by the elderly," *Springer Plus*, vol. 5, no. 1, p. 624, 2016.

[13] G. Guerrero-Ulloa, C. Rodríguez-Domínguez, and M. J. Hornos, "IoT-based system to help care for dependent elderly," in *Communications in Computer and Information Science*, vol. 895, pp. 41–55, Springer Verlag, 2019.

[14] M. Shishehgar, D. Kerr, and J. Blake, "The effectiveness of various robotic technologies in assisting older adults," *Health informatics journal*, vol. 25, no. 3, pp. 892–918, 2019.

[15] R. Zhong and P. L. P. Rau, "Are cost-effective technologies feasible to measure gait in older adults? A systematic review of evidence-based literature," *Archives of gerontology and geriatrics*, vol. 87, p. 103970, 2020.

[16] N. M. Napi, A. A. Zaidan, B. B. Zaidan, O. S. Albahri, M. A. Alsalem, and A. S. Albahri, "Medical emergency triage and patient prioritisation in a telemedicine environment: a systematic review," *Health and Technology*, vol. 9, no. 5, pp. 679–700, 2019.

[17] E. Moguel, J. Berrocal, J. M. Murillo et al., "Enriched elderly virtual profiles by means of a multidimensional integrated assessment platform," *Procedia Computer Science*, vol. 138, pp. 56–63, 2018.

[18] R. Roman, J. Zhou, and J. Lopez, "On the features and challenges of security and privacy in distributed Internet of things," *Computer Networks*, vol. 57, no. 10, pp. 2266–2279, 2013.

[19] V. Tang, K. L. Choy, G. T. Ho, H. Y. Lam, and Y. P. Tsang, "An IoMT-based geriatric care management system for achieving smart health in nursing homes," *Industrial Management and Data Systems*, vol. 119, no. 8, pp. 1819–1840, 2019.

[20] S. Bonilla, E. Moguel, and J. Garcia-Alonso, "Facial recognition of emotions with smartphones to improve the elder quality of life," in *Communications in Computer and Information Science*, vol. 1016, pp. 15–25, Springer Verlag, 2019.

[21] J. Rojo, J. L. Herrera, E. Moguel, and J. Hernández, "A microservice architecture for access control based on long-distance facial recognition," in *Communications in Computer and Information Science*, vol. 1185, pp. 219–229, Springer, 2020.

[22] S. Bonilla, E. Moguel, J. Garcia-Alonso, J. Berrocal, and J. M. Murillo, "Emotion identification with smart-phones to improve the elder quality of life using facial recognition techniques," in *Exploring the Role of ICTs in Healthy Aging*, D. Mendes, C. Fonseca, M. J. Lopes, J. García-Alonso, and J. M. Murillo, Eds., pp. 178–193, 2020.

[23] H. Ali and H. Li, "Evaluating a smartwatch notification system in a simulated nursing home," *International Journal of Older People Nursing*, vol. 14, no. 3, 2019.

[24] A. Huion, V. Decalf, C. Kumps, N. De Witte, and K. Everaert, "Smart diapers for nursing home residents with dementia: a pilot study," *Acta Clinica Belgica: International Journal of Clinical and Laboratory Medicine*, vol. 74, no. 4, pp. 258–262, 2019.

[25] C. Rotariu, R. G. Bozomitu, and H. Costin, "Assistive technologies to support communication with neuro-motor disabled patients," in *Recent Advances in Intelligent Assistive Technologies: Paradigms and Applications*, pp. 29–60, Springer, 2020.

[26] F. Delmastro, C. Dolciotti, D. L. Rosa et al., "Experimenting mobile and e-health services with frail MCI older people," *Information*, vol. 10, no. 8, p. 253, 2019.

[27] A. Barriga, J. Conejero, J. Hernández, E. Jurado, E. Moguel, and F. Sánchez-Figueroa, "A vision based approach for building telecare and telerehabilitation services," *Sensors*, vol. 16, no. 10, 2016.

[28] W. Moyle, "The promise of technology in the future of dementia care," *Nature Reviews Neurology*, vol. 15, no. 6, pp. 353–359, 2019.

[29] C. Davidson, S. Loganathan, L. Bishop et al., "Scalability of an IT intervention to prevent pressure ulcers in nursing homes," *Journal of the American Medical Directors Association*, vol. 20, no. 7, pp. 816–821.e2, 2019.

[30] E. Moguel, J. Berrocal, J. Garcia-Alonso, D. Flores-Martin, J. Galan, and J. M. Murillo, "Extensible environment for monitoring and detecting symptoms of depression," *Proceedings 2019 IEEE Smart-World, Ubiquitous Intelligence and*

Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Internet of People and Smart City Innovation, Smart World/UIC/ATC/SCAL650 COM/IOP/SCI 2019, , pp. 1870–1875, Institute of Electrical and Electronics Engineers Inc, 2019.

[31] E. Moguel, J. Berrocal, and J. García-Alonso, "Systematic literature review of food-intake monitoring in an aging population," *Sensors*, vol. 19, no. 15, p. 3265, 2019.

[32] E. Moguel and J. García-Alonso, "Foodscan: food monitoring through purchase tickets analysis using the smart-phone," in *Communications in Computer and Information Science*, vol. 1185, pp. 36–43, Springer, 2020.

[33] E. Moguel, J. García-Alonso, and S. Laso, "Yourpantry: food monitoring through pantry analysis using the smartphone and making use machine learning and deep learning techniques," in *Communications in Computer and Information Science*, vol. 1185, pp. 3–10, Springer, 2020.

[34] M. Jesús-Azabal, J. Rojo, E. Moguel et al., "Voice assistant to remind pharmacologic treatment in elders," in *Communications in Computer and Information Science*, vol. 1185, pp. 123–133, Springer, 2020.

[35] J. Berrocal, J. Garcia-Alonso, J. M. Murillo, and C. Canal, "Rich contextual information for monitoring the elderly in an early stage of cognitive impairment," *Pervasive and Mobile Computing*, vol. 34, pp. 106–125, 2017.

[36] C. Ji, Y. Li, W. Qiu, U. Awada, and K. Li, "Big data processing in cloud computing environments," in *2012 12th international symposium on pervasive systems, algorithms and networks*, pp. 17–23, San Marcos, TX, USA, 2012.

[37] D. Flores-Martin, J. Berrocal, J. Garcia-Alonso, and J. M. Murillo, "Towards a runtime devices adaptation in a multi-device environment based on people's needs," in *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (Per Com Workshops)*, pp. 304–309, Kyoto, Japan, 2019.

[38] L. Oneto, J. L. Ortiz, and D. Anguita, "Chapter 7-constraint-aware data analysis on mobile devices: an application to human activity recognition on smartphones," in *Adaptive Mobile Computing*, M. Migliardi, A. Merlo, and S. A. H. Baddar, Eds., pp. 127–149, Intelligent Data-Centric Systems, Academic Press, Boston, 2017.

[39] J. Rojo, D. Flores-Martin, J. Garcia-Alonso, J. M. Murillo, and J. Berrocal, "Automating the interactions among IoT devices using neural networks," in *2020 IEEE International Conference on Pervasive Computing and Communications Workshops (Per Com Workshops)*, pp. 1–6, Austin, TX, USA, 2020.

[40] D. Flores-Martin, S. Laso, J. Berrocal, C. Canal, and J. M. Murillo, "Allowing IoT devices collaboration to help elderly in their daily lives," in *International Workshop on Gerontechnology*, pp. 111–122, Springer, 2019.

[41] G. Susto, M. Terzi, C. Masiero, S. Pampuri, and A. Schirru, "A fraud detection decision support system via human on-line behavior characterization and machine learning," in *2018 First International Conference on Artificial Intelligence for Industries (AI4I)*, pp. 9–14, Laguna Hills, CA, USA, 2019.

[42] B. M. Hasan Alhafidh, A. I. Daood, and W. H. Allen, "Prediction of human actions in a smart home using single and ensemble of classifiers," in *Southeast Con 2018*, pp. 1–8, St. Petersburg, FL, 2018.

[43] C. Asawa, K. Zakka, B. Pan, L. Zhou, Y. Zhang, and X. Liu, *CS231n Convolutional Neural Networks for Visual Recognition*https://cs231n.github.io/neural-networks-3/#loss.

[44] R. Kazman, M. Klein, and P. Clements, *Atam: Method for Architecture Evaluation*, Carnegie-Mellon Univ Pittsburgh PA Software Engineering Inst, 2000.

[45] J. L. Herrera, J. Berrocal, J. M. Murillo, H. Y. Chen, and C. Julie, "A privacy-aware architecture to share device-to-device contextual information," in *IEEE International Conference on Smart Computing*, Bologna, Italy, 2020.

Chapter 5

SOWCompact: A federated process mining method for social workflows

Authors: *Javier Rojo, Jose Garcia-Alonso, Javier Berrocal, Juan Hernández, Juan Manuel Murillo, Carlos Canal.*

Publication type: *Journal article.*

Journal: *Information Sciences.*

Year of publication: *2022.*

DOI: *10.1016/j.ins.2022.02.035*

2021 JCR IF (Rank): *8.233 (Q1 16/164)*

Information Sciences 595 (2022) 18–37

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

SOWCompact: A federated process mining method for social workflows

Javier Rojo [b,*], Jose Garcia-Alonso [b], Javier Berrocal [b], Juan Hernández [b], Juan Manuel Murillo [b], Carlos Canal [a]

[a] ITIS Software, Universidad de Málaga, Spain
[b] University of Extremadura, Spain

ARTICLE INFO

Article history:
Received 9 March 2021
Received in revised form 14 February 2022
Accepted 18 February 2022
Available online 24 February 2022

Keywords:
process mining
Pattern discovery
Social workflows
Federated process mining

ABSTRACT

The exaggerated use of smartphones and growing informatization of the environment allows modeling people's behavior as a process, namely, a social workflow, where both individual actions and interactions with other people are captured. This modelling includes actions that are part of an individual's routine, as well as less frequent events. Although infrequent actions may provide relevant information, it is routine behaviors that characterize users. However, the extraction of this knowledge is not simple. Current process mining techniques face problems when analyzing large amounts of traces generated by many users. When very different behavioral patterns are integrated, the resulting social workflow does not clearly depict their behavior, either individually or as a group. Proposals based on frequent pattern mining aim to distinguish traces that characterize frequent behaviors from the rest. However, tools that allow grouping/filtering of users with a common behavior pattern are needed beforehand, to analyze each of these groups separately. This study presents the so-called federated process mining and an associated tool, SOWCompact, based on this concept. Its potential is validated through the case study called activities of daily living (ADL). Using federated process mining, along with current process mining techniques, more compact processes using only the social workflow's most relevant information are obtained, while allowing (event enabling) the analysis of these social workflows.

1. Introduction

The development of process mining enables access to new frontiers in the analysis of social workflows (SOW) [17]. The exaggerated use of mobile, particularly smartphones, and Internet of Things (IoT) devices is placing a huge amount of the sensors around people. Owing to this growing infrastructure unprecedented volumes of information regarding people's lives have become readily available. Representing all this information in a chronological log allows us to consider a person's life as a process execution, namely, the process of that individual's life. Subsequently, routine behaviors and patterns of conduct can be inferred. The analysis of thousands or millions of these executions pave the way for determining how individuals and groups behave; thus, providing new perspectives on SOWs [17]. Subsequently, it is possible to further analyze patterns,

* Corresponding author.
E-mail addresses: javirojo@unex.es (J. Rojo), jgaralo@unex.es (J. Garcia-Alonso), jberolm@unex.es (J. Berrocal), juanher@unex.es (J. Hernández), juanmamu@unex.es (J.M. Murillo), carloscanal@uma.es (C. Canal).

https://doi.org/10.1016/j.ins.2022.02.035

such as calculating the probability of an individual performing a given activity. The corresponding activity is defined as the next activity of an individual who previously engaged in a specific sequence of activities, or the most likely behaviors within a particular social group. Examples of systems relying on such techniques are those that analyze interactions among individuals to improve recommendation systems [36], how customers move in shopping malls to determine preferred destinations [14], or assess patient routines to establish causal relationships in healthcare applications [49].

Although applying process mining to analyze SOWs can be particularly useful, certain facts must be considered first. Process mining techniques and algorithms assume that traces in the logs correspond to instances of reality that tend to be governed by a defined process. However, when it comes to social flows, each trace corresponds to a behavior of an individual, which is not necessarily deterministic. Therefore, a behavior does not need to match that of other individuals. When it does, it is highly likely that this is a coincidence [17]. Using process mining techniques on a set of traces when there is no clearly defined process usually leads to unrealistic, abnormally complex, and unreadable [21] process models with many states and transitions [32]. These are difficult to analyze, and will not provide relevant information about any of the social groups involved.

For these reasons, it is necessary to adapt process mining techniques to the specific features of SOWs. This study presents a methodology called federated process mining (FPM), which applies process mining techniques to the analysis of complex SOWs based on the concept of software federation: A group of semi-autonomous devices operating together for a common purpose. Consequently, each member of the federation carries out their task individually, before all results are pooled. For the case under discussion, each individual's data will be processed independently. Then, the integrated data of the users that form an SOW, based on common behaviors, will be analyzed. Using the computational capabilities of contemporary smartphones, each individual behavioral process model can be discovered locally. This design decision assumes that the behavior of an individual is not erratic [16], and thus the resulting models avoid unnecessary complexity. By querying smartphones, only the relevant individuals, those that show patterns of conduct of interest, are selected, and their traces are aggregated to generate a workflow for this particular social group. This approach avoids unwanted variability, resulting in higher quality process models of SOWs.

Utilizing smartphones to perform the first phase of the proposed methodology limits the proposal to the analysis of SOWs generated by data stored on such devices. However, the exaggerated presence and constant use of these devices in people's daily lives make them perfect candidates for the analysis of SOWs.

To demostrate how the proposed method can be used and its benefits, we present SOWCompact, a tool for federated process mining that uses existing process mining tools and algorithms in a federated architecture. SOWCompact has been validated with a case study named activities of daily living (ADL) [24], using an existing dataset that contains event logs on ADL from real users.

This research suggests a way to successfully apply process mining techniques to the analysis of SOWs using a federated method to reduce the complexity of the generated models without a quality loss of models. Additionally, by leveraging mobile computing resources, this method reduces the amount of information sent to the process mining servers, which reduces both data traffic and, more importantly, computational load.

The novelty of this proposal lies in the distribution of the social workflow process mining procedure in two phases through a distributed architecture. It leverages of the computational capabilities of the smartphones in performing an initial individual process mining phase. In addition, this distributed architecture enables adopting a new filtering method based on the identification of users that meet a behavior of interest. This approach creates more compact models that represent more accurately the behavior of a specific social group.

The remainder of this paper is structured as follows. Section 2 introduces the motivations behind this study. Section 3 highlights the weaknesses of the current state-of-the-art methods both regarding process mining and social workflows, providing crucial background information on the novelty of our approach. Section 4 describes the federated process mining method and proposes a starting point architecture for tools using this method. Section 5 introduces the so-called SOWCompact, describes its main features, and demonstrates how it can be used to successfully analyze SOWs. A methodology to assess of the proposed approach in any case study is presented in Section 6. In Section 7, the results of applying this methodology to assess the validity of our proposal in the case study described in Section 6.1 are presented. This is followed by an analysis and discussion presented in Section 8. Finally, Section 9 concludes this study and discusses future research directions.

2. Motivation

Social computing (SC) is the area of information technology that deals with the interrelations between social behavior and computer systems [46]. Initially, SC mainly focused on processing and analyzing social information [38], which is defined as the fingerprint left behind by people when performing daily activities. However, the term has progressively evolved toward a wider meaning that includes using computer systems to support any type of social behavior, where humans are the main protagonists; not only as beneficiaries but also as active players [9].

The exaggerated use of smartphones among a large part of the world's population makes these devices ideal for virtually representing their users [30]. Performing SC tasks on users' smartphones allows harnessing the computing power of each user's device while preserving the privacy of the user data [18] and reducing power consumption [4]. We have also worked on the deployment of application programming interfaces (APIs) on such devices to distribute computing processes, which facilitates communication and data requests between the server and smartphones [26].

In the context of SC, social media mining is defined as the process of representing, analyzing, and extracting patterns and trends from social media data. Its objective is to generate detailed profiles of individuals and social groups [35].

Social workflows (SOWs) model describes how a group of people performs a set of activities [17]. The sequence of activities performed by each individual during the SOW is represented by a trace.

Accordingly, activities of daily living (ADL) are the daily routine activities of a person performs [24] (e.g., eating, drinking, walking, or exercising). Studying these activities can be contemplated in SC, because the process that follows a person performing their ADL can be considered an SOW.

The application of process mining techniques to ADL SOWs allows the mining of processes carried out by users in their daily activities. Although each person's daily routine can drastically differ from that of the people around them, often we can observe behaviors that are common to certain groups. Identifying people who are part of a particular group would allow us to establish, for instance, certain behaviors that these people have in common. Thus, the behavior of a particular group would constitute a specific SOW, different from that of any other group. The identification of this SOW and its associated processes may be beneficial in different fields. For example, in medicine, such an approach could ensure the effective monitoring users' health and habits, which would improve the results of preventive medicine and patients' quality of life [49]. This approach may also help identify deficiencies or anomalies in people's behavior [48].

However, while process mining techniques can positively contribute to SC, they remain far from providing satisfactory results. The reason for this is illustrated in Fig. 1, where the model generated using a heuristic algorithm for process mining is demonstrated. This model integrates the traces of the ADL SOWs of only seven different users and monitors their activities for an average period of ten days. Observe that, although the number of users and time frame are limited, trying to discover frequent patterns using that model is difficult. For example, three out of the seven users go *shopping* before preparing a meal (*meal preparation*). This simple pattern that is composed of only two activities is difficult to identify among many different patterns that intersect with it because other users' patterns also include these activities. Furthermore, it is even more difficult to identify other patterns that are met simultaneously with the one initially queried.

To solve this problem, a novel method of pattern extraction is required. Instead of processing the traces of all users, a better solution is to consider only the traces of a group of users that already possess the required pattern. To do this, we need to discover the individual model of the behavior of each user. Then, these individual models are filtered to identify which users exhibit the required pattern.

3. Related work

Before explaining the solution proposed in this study, it is necessary to review the existing literature in the field of process mining applied to social workflows and events carried out by users that correspond to activities with a certain degree of variability. Moreover, using smartphones to carry out these tasks should be discussed.

Process mining techniques are divided into different categories based on their main goals. Process discovery is one such technique that is used to generate a process model based on the behavior captured in a log [1]. This study focuses on this type of process mining to discover the processes contained in the data captured by each smartphone, so that they can be processed further later.

In the process discovery domain, several studies have attempted to leverage the models generated to perform workflow analysis. Van der Aalst et al. [45] proposed a solution based on process discovery to estimate the waiting time on a phone call. These systems have also been used for commonly in recommendation systems. Schonenberg et al. [36] proposed a recommendation service based on a log, in which they applied different methods to determine recommendations.

Recently, with the increasingly exaggerated use of mobile devices, process mining is being applied to problems involving data obtained from these devices. For instance, proposals such as that of Sztyler et al. [43] demonstrate how process mining can be applied to data collected by activity sensors to discover user processes. This approach represents the most frequent relationships between the daily activities carried out by the user and allows us to observe the acceptance and deviation from the model that should originally be followed. The activities performed are detected through sensors connected to the user's smartphone. Another similar proposal uses process mining of data obtained from healthcare sensors connected to the smartphone to self-monitor the user's health [42]. Hwang and Jang [22] used process mining to analyze the changes in customers' movement patterns in a fashion retail store following certain changes in the position of mannequins. Other studies have focused on the safety of mobile applications, for example, Bernardi et al. used process mining to detect whether an application contained malicious software [3]; if so to which malware family it belonged.

However, these studies focus on integrating data obtained from different sources in a server using many already existing tools, where all data are analyzed as a set using a process mining tool. ProM[1] is a widely used graphical interface tool that is compatible with numerous algorithms. Other tools, such as PM4PY[2], offer interface free solutions that allow integrating process

[1] https://www.promtools.org/doku.php
[2] https://pm4py.fit.fraunhofer.de/

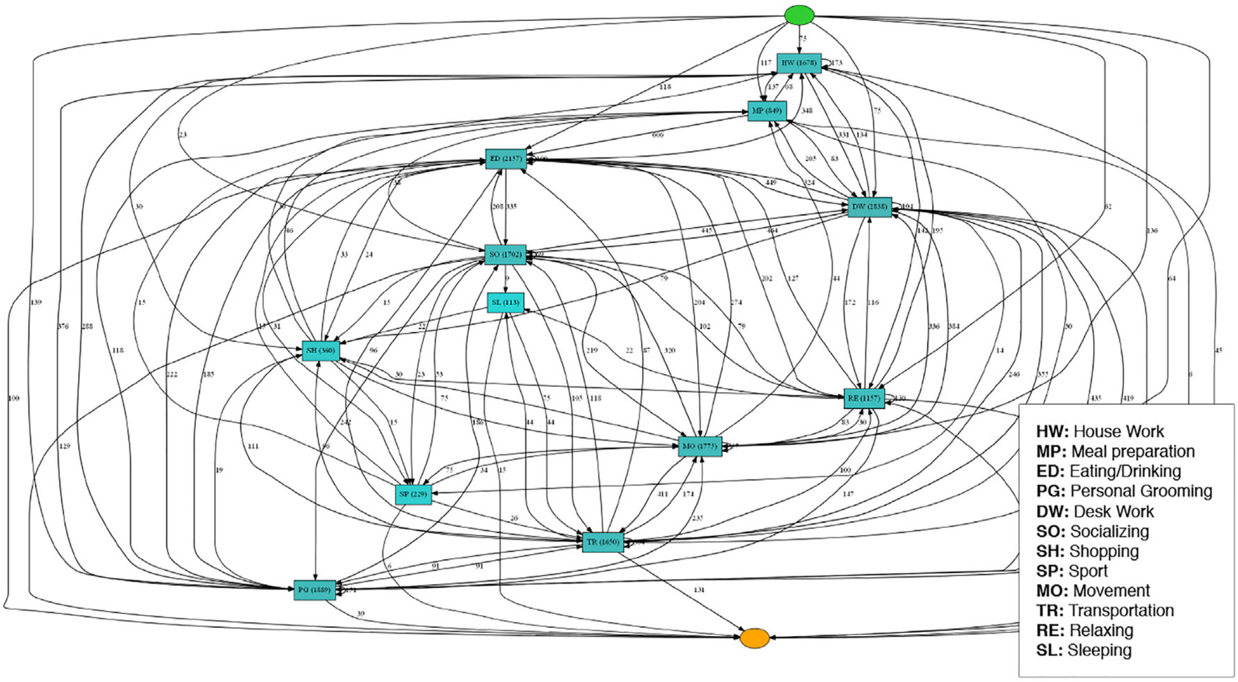


Fig. 1. Spaghetti model generated from a SOW with classic process mining techniques.

mining into other systems using Python. BAB [41] offers a cloud solution for analyzing large amounts of data using its own process analysis algorithms.

However, generating models where all data are integrated on the server implies integrating the data obtained from different users based on very different behaviors. This adds noise to the models, which is a main problem in process discovery applications [2]. In addition, if the amount of data to be integrated is large, the server used for analysis will require a sufficiently large capacity.

Solutions to such problems already exist in the literature. Regarding the noise, there are solutions that alleviate it by extracting frequent behavioral patterns from the generated model. Subsequently, the models become more understandable and of higher quality. These proposal types are encompassed under the term frequent pattern mining. This approach was adopted by Chapela-Campa et al. [8], who suggested using an algorithm over the generated models to identify the most executed parts of the models. The algorithm they proposed was based on the frequency at which the arcs of the entire model structure were executed. The resulting models only contained the most frequently observed activities and relationships. Other proposals for detecting frequent patterns were based on the frequency at which each single arc of the model was executed. These proposals used the values of the arcs computed by tools such as Disco with heat maps, or by algorithms such as Heuristic Miner [47]. Consequently, the newly generated models include only the arcs with a frequency higher than a given threshold. However, considering only the individual weights of the arcs causes problems because the causality between tasks is not considered [8].

Other studies have addressed the efficiency problems that occur in the server. For instance, the proposal of Loreti et al. aimed to solve the problem of analyzing large logs by means of computer clusters [28], using techniques such as MapReduce. Other proposals have tried to leverage the computing capacity of modern mobile devices to perform some phases of process mining. Using mobile devices as process mining tools, that serve as event collectors, was suggested by Medeiros et al. [12]. However, process mining using mobile devices has not advanced along with advances in the hardware technologies of these devices. Future research could follow up on this approach and analyze users' data kept on mobile phones, thus, generating a model for each user on their own devices. This approach of constructing personal models could perform the initial phase of analysis and, if necessary, could be integrated with other user models on a server. This methodology was applied in Kim and Kim's proposal [25], which conducted process mining on a server, using Disco tool, to analyze user behavior through mobile commerce application logs generated in Android OS. Using a hybrid architecture, each user log was analyzed on the device where it was generated. Later, on the server, users with similar shopping patterns could be selected and analyzed together, based on the existence of common patterns in their process model.

Although there are proposals that address noise in integrated processes and proposals to adopt some process mining phases in mobile devices, a full mining of individual user data separately on smartphones has not been conducted. Even though a proposal of this type addresses the two problems previously discussed, to the best of our knowledge, there are no frameworks that can perform of all tasks of process discovery in mobile devices. However, using this type of approach has several advantages. First, once a user's model is generated, it would be possible, for instance, to check which pattern each user met (if known—classification) or which different patterns existed (if not known —clustering). Next, the integration of user data with similar patterns could be performed. Subsequently, possible noise ocurring from analyzing logs containing actions of users with different patterns would be eliminated. Such a proposal could be complemented with current research on frequent pattern mining, which would improve the results offered by both. Second, by first analyzing each user data separately and only analyzing these results in aggregate, better efficiency could be achieved.

Discovering and grouping users based on the observation of their behavioral patterns can be done through process mining clustering techniques, which have commonly been used in practice [13]. For example, Song et al. proposed in [40] using clustering over a profile that characterizes each trace. Thus, the traces of all users are grouped into different clusters according to their profiles. The profile is composed of different features derived from traces, such as number of events and concrete events that appear in the trace. Other proposals, such as that of Jablonski et al. [23], are based on a similar characterization of traces. Cirne et al. [10] suggested a different approach, using clustering techniques alongside model discovery to generate new models with less noise in algorithms such as Alpha.

However, notice that the objectives of these techniques differ from those pursued in this study. If our aim were to create a method to group all existing users based on their different patterns in individual models generated in their smartphones, we would use clustering techniques. However, we aim to be able to ascertain which users meet an already known behavior in the model to select and analyze them exclusively. This is closer to the results that could be expected from the classification techniques applied to process mining than those of clustering techniques. To the best of our knowledge, there are no previous techniques or methods for filtering users based on a behavior of interest, nor for taking advantage of a distributed architecture, based on the federation of different smartphones, which is the goal of our proposal.

Thus, it is necessary to define a proposal that allows conducting an analysis focused on a group of users who share a common pre-determined behavior. Assuming that mobile devices generate most of the information that will be included in the social workflows of social groups to which the user belongs, it would be convenient to utilize the computational power of these devices to optimize the process of selecting which users are part of a social group based on whether they comply with the desired behavior.

None of the analyzed proposals performed this type of task. To achieve a more efficient analysis of social workflows using current process discovery algorithms, it is necessary to introduce a new proposal that covers all these aspects.

3.1. Pattern query languages

Another important topic for which the current the literature must be reviewed is the representation of behaviors of interest, namely Frequent Patterns, in a language that can be understood by all components of federated process mining. Different alternatives have been proposed to specify this language.

On the one hand, several proposals have considered process mining models in a textual language. Frequent patterns can be considered as fragments of the user models, hence, models themselves. Accordingly, solutions based on using declarative languages [33] have been suggested in the literature. Declarative languages represent models as a set of declarative constraints that limit the number of execution alternatives in a process. An example of this can be found in the work of Schönig et al. [37], which proposes a process discovery technique for models represented using the Multi-Perspective Declare (MP-Declare) [7] declarative language. The proposed process discovery technique follows an SQL-based process mining approach. However, after analyzing different alternatives of declarative languages, using a solution based on these languages was discarded. This was owing to their proposal being based on imperative languages [33] to represent the models because of their better expressiveness. Therefore, representing the models and frequent patterns in different language types may not be the best option. Because such applications suffer from and increased complexity when translating models from one representation to another. Other solutions have developed complete frameworks performing queries over process models. This is the case of Polyvyanyy et al. [34], who developed a framework to perform optimized queries over process repositories, where the models regarding which queries will be consulted are stored in. Yongsiriwit et al. [50] proposed a query language that allows for consulting on which fragments of models an activity appears. This language complements an approach aimed at generating a neighborhood context for each activity based on the execution order of the activities involved in the process. More specifically, it extracts the execution order of activities to build a neighborhood context for each activity.

However, there are alternatives such as that of Meddah et al. [29]. Their proposal uses a syntax similar to that of regular expressions to define sequences of events that must appear in the model and connects those events with certain operations. Accordingly, linear temporal logic (LTL) [15] provides a well-defined and widespread language that allows easy representation of event sequences in time, similar to the function of processes.

The underlying premise of regular expressions, with LTL syntax or other, to represent sequences of events is the same as that of declarative languages to represent process mining models in a textual language: A sequence of events that must be met in the model definition as a constraint. Therefore, this sequence of events can be understood as the representation of a partial model that must be contained within a user model or within a model that would be generated from a trace to consider that this user and trace comply with a behavior of interest.

In addition, solutions based on regular expressions provide some advantages over solutions based on declarative languages, that is, they are simpler in defining the rules and integrating the support of this language in the pattern query resolver. Moreover, they benefit the generated model of the individual process mining component of the framework proposed in this study. Therefore, a solution of this type is the most suitable for the proposed method.

4. Federated process mining (FPM)

The challenges of classic process mining techniques to when analyzing complex SOWs resulting from integrating data from users without a common behavior pattern have been presented above. To address these difficulties, we propose using the so-called federated process mining (FPM), where process mining is performed in two steps: First, individual mining; then, mining user groups with a common behavior. The first step allows individuals to be filtered to determine those who comply with the behavior of interest in an SOW. Once the individual data is filtered out, only the SOWs resulting from users who meet the desired behavior are analyzed. This process assumes that each time there is only one group of interest, that is, only the individuals that comply with the behavior of interest are analyzed. Data from users that do not belong to the group of interest are excluded and analyzed only when a new group is formed according to a new searched behavior.

Federated process mining uses the computational power of the user' devices to perform the first phase, which reduces the amount of data that needs to be processed to analyze the SOW. Owing to this filter, federated process mining techniques offer more compact models without loss of quality. Fig. 2 illustrates an example of the model generated for the same SOW in Fig. 1 using filtering. These figures, although difficult to read owing to their size (a higher resolution version is provided as additional material), allow us to compare the readability of the models and visually compare the models generated from the same SOW considering:

- A classic process mining approach, in which all user data are integrated into a single model (Fig. 1).
- A federated process mining approach that filters users and integrates only the traces that comply with the behavior of interest (Fig. 2).

In the second case, 33% of the arcs were reduced by filtering users and traces compared to the model generated using classic non-federated process mining. This means that the average of approximately 10 arcs per event, with 116 arcs in total, is reduced to seven when filtering users and traces, with 78 arcs in total. A higher number of arcs going in and out of an event means a low-precision model that accepts almost any execution order. The sum of the weights of these arcs is also reduced to 23% of that of the classic model. This demonstrates the disadvantage of the models generated with classic non-federated process mining, which may contain any process, while the filtered approach offers results closer to the reality of the concerned users for a given SOW.

The heuristic nets illustrated in Figs. 1 and 2 depict real models generated by applying the two different process mining approaches to the case study data, ADL event logs.

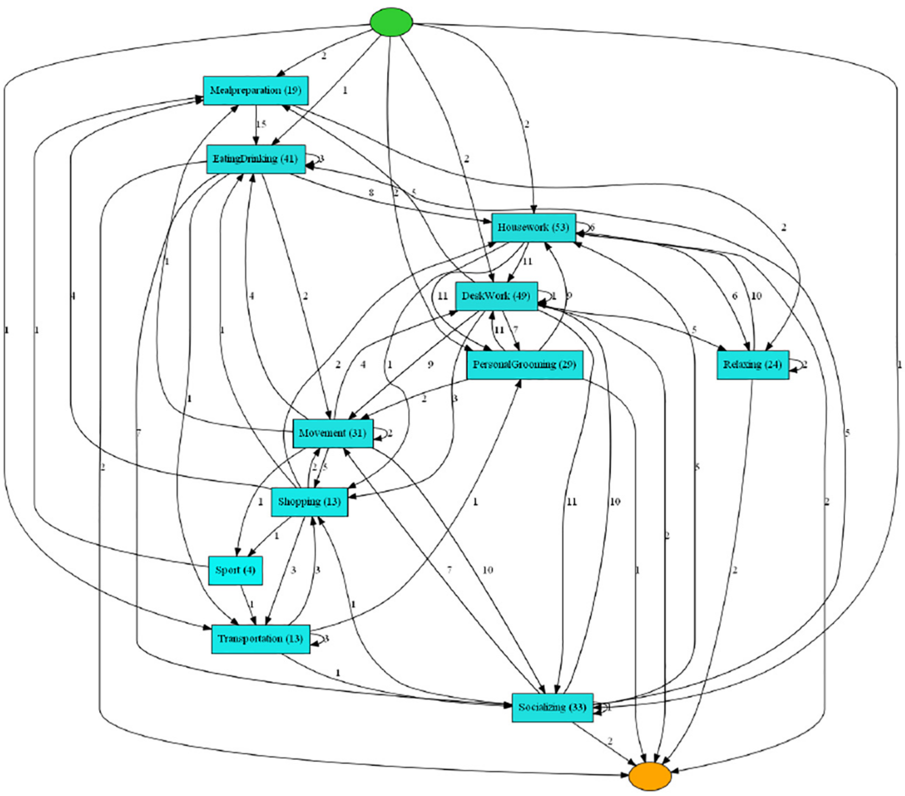


Fig. 2. SOW model discovered using a FPM approach.

This dataset, presented in more detail in Section 6.1, was gathered by Sztyler et al. [43], and stores seven different event logs that represent the actual behavior of seven different individuals for an average of ten days. This includes twelve different daily activities that are common to most people's routines.

4.1. Federated process mining architecture

To facilitate the development of FPM tools, a novel architecture is proposed in Fig. 3, based on three main components: First, the individual process mining component, which integrates the traces of an individual in her smartphone and produces the corresponding behavioral process model; Second, the social process mining component, which selects the users to be analyzed based on the presence of a certain pattern in their behavioral process models. Once it obtains the information of the users that meet the pattern, mining is performed to obtain the process model for the SOW that these users represent; Finally, the federated process mining aggregator (FPM aggregator) component supports the connection between these two components, asking smartphones for the individuals possessing the frequent pattern in their behavioral models and collecting their traces for the social process mining component. This communication is performed using a query language that can be interpreted by both components.

The workflow presented in Fig. 3 is described as follows:

1. The user's smartphone creates an event log by gathering data from the sensors or applications. Movement traces from the GPS, activity levels from the accelerometer, application usage events, or WIFI connectivity are examples of user information provided by the smartphone that can be collected during this stage. The developers of the applications where federated process mining is utilized must implement a module to generate this log.
2. With this event log, the user's smartphone applies a process mining algorithm that generates a model for the user's behavior represented in the event log.
3. Only then, the server can request data from the user event log using this model. To do this, the server defines a query with a pattern (frequent or not) that must be met by the models of the users from whom it will gather data. This query is sent to all user smartphones using the FPM aggregator.
4. When the smartphone of a user receives the query, it processes the user's model to check whether it meets the pattern. If it does, the smartphone processes the event log to select the specific traces that meet the pattern sought after. Traces are not directly processed because this would be inefficient for large event logs or if queries with different behavioral patterns were being sent frequently.

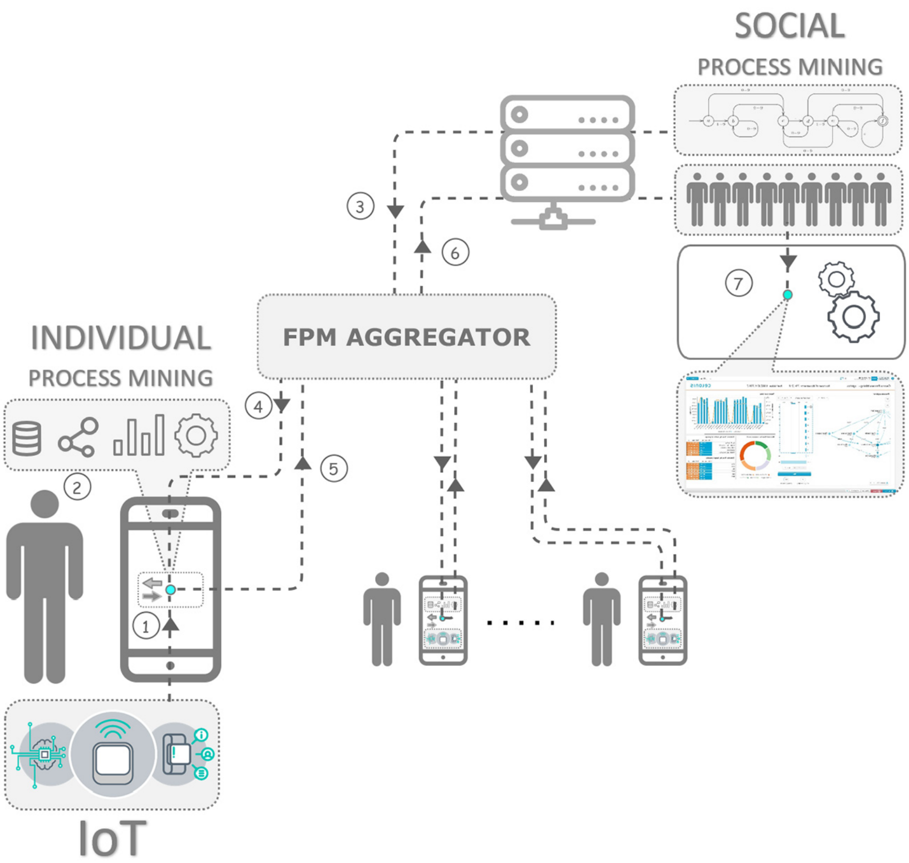


Fig. 3. Architecture for federated process mining.

5. Traces that meet the pattern are sent to the FPM aggregator, along with the query and user to which they correspond. The FPM aggregator is responsible for integrating the data of different users' traces that meet the query pattern.
6. The integrated data are stored in the server.
7. Using these integrated data, a new phase of process mining is carried out. In this new phase, a model representing the behavior of a single social group (SOW) is obtained.

By following this process, a social group is determined based on the users who meet a certain pattern defined in the query sent to the users' devices. As can be understood this process, the behavioral pattern of interest that the users must comply with, which is reflected in the query, must be known to the analyst beforehand, that is, before launching the federated process mining process. Only user data that meet the pattern of interest will be sent for further analysis and become part of the resulting SOW. Therefore, only users that comply with the requested behavioral pattern are selected. Then, the analyst is able to analyze their information and that of the remaining patterns that they have in common if relevant. The patterns that might exist between selected and not selected users are no longer relevant, from the moment that the unselected users do not meet the queried behavior. Therefore, the analysis of their information and other patterns that they might share between them or with the users who do meet the pattern of interest is not necessary.

5. SOWCompact: a federated process mining tool

The federated process mining method and FPM architecture have been described earlier. Therefore, we now introduce the so-called SOWCompact, which is a complete FPM tool. Its components are described as follows:

Individual Process Mining (Fig. 4). This component was implemented as an Android application. It runs on each user's smartphone and is responsible for generating the individual models and checking whether these users meet the patterns that the server seek. To do this, the application employs an individual process mining module, which can be added to any smartphone application that contains an event log to perform the process mining. Therefore, any developer who wants to perform federated process mining using their application only needs to import this module and link it to their own event log files. Developers must generate these event log files outside the individual process mining module, considering the relevant information. Considering that the variety of information with which these event logs can be generated is only limited the creativity of the team behind the application, SOWCompact has not implemented any module that generates an event log in a user application. The only requirement is that event logs must be generated in the XES format [19]. This format, one of the most frequently used in process mining, is an extension of XML, which employs a notation containing a set of well-known tags to represent data as traces of events. Therefore, event logs in this format are visually understandable and widely compatible with process mining tools.

To generate a model from the log file, a version of the Alpha algorithm [11], which considers loops in the traces, is used. This algorithm has been chosen because it has an existing implementation[3] in Java that can be employed in Android applications. Nevertheless, other process mining algorithms can be used instead. For replicability, the algorithm, adapted for use as a library in an Android application, can be found here [4].

Once the model is generated, it is stored in the smartphone and periodically updated to include more recent user behavior.

The other component of the individual process mining module is the pattern query resolver, which processes the server queries received through the FPM aggregator. This module checks whether the user's model meets a given pattern. In this case, it collects traces that contain the pattern and sends them to the server.

The use of a process mining model in this component ensures that all user traces only need to be processed on the smartphone if the specific user meets the desired pattern. Subsequently, traces from users that do not meet the pattern will not be processed again for each received query.

Social Process Mining. This component is deployed on the server side, and its source code can be found here [5]. It is responsible for generating the SOW models with the data integrated by the FPM aggregator using a process mining tool. Specifically, *Process Mining for Python* (PM4PY) was chosen as the mining tool because it is free and widely used in the process mining community. It also allows for automating the process of generating models using Python scripts. However, other process mining tools can be used instead. From the algorithms available in this tool, the heuristic miner algorithm [47] has been used, because it is a suitable for working with real-life data when there are not many different events [20]. According to the first phase of individual process mining, the number of different events that these traces will contain will be smaller if all data are analyzed directly on the server. As is the case with the tool, any other algorithm can be employed instead.

Likewise, this component can be replaced by any other process mining server that performs process mining on event log data. It would only be necessary to add a module to define queries based on patterns and to receive the traces of all the users that meet the requested pattern.

[3] https://github.com/atanasovskib/AlphaAlgorithm
[4] https://bitbucket.org/spilab/androidalpha
[5] https://bitbucket.org/spilab/serverapp

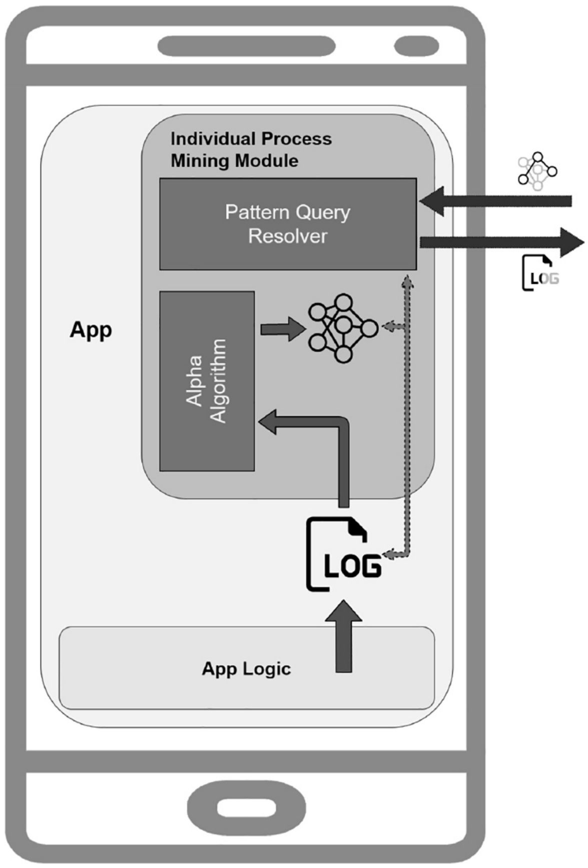


Fig. 4. Internal architecture of the individual process mining component.

FPM Aggregator. This component is deployed between the individual process mining and social process mining components, allowing communication between them. It is responsible for requesting the data that meet a pattern from the users' devices and adding the response data sent to the server from the users who meet the required pattern. The FPM aggregator was implemented using our previous proposal for the deployment of mobile APIs [26].

Pattern Query Language. This language manages the interaction between the individual process mining and the social process mining components through the FPM aggregator. Specifically, it is used to specify event patterns. For this purpose, linear temporal logic (LTL) [15] was selected.

LTL is a well-defined modal temporal logic that allows defining linear time conditions referring to future events. It also establishes a relationship with other formal languages, such as propositional logic, because it utilizes propositional variables and logical operators along with the temporal modal operators it defines. Specifically, the operators that LTL offers are:

- ◯**A** (next): event A must happen in the next state.
- ◆**A** (finally): event A must happen in some of the following state.
- □**A** (globally): event A must occur in all the following states.
- **A** $\mathscr{U}$ **B** (until): event A will continue to happen at least until event B, in a current or future state.
- **A** $\mathscr{R}$ **B** (release): event B will continue to happen at least until and including the moment when event A occurs.
- **A** $\mathscr{W}$ **B** (weak until): event A must occur at least until event B occurs; if B never happens, A must remain forever.
- **A** $\mathscr{M}$ **B** (strong release): event B must happen up to and including the point where event A occurs, which must be maintained in the current or future position.
- **Logical operators**: LTL supports propositional logic, thus, its operators can be used to write the LTL formulas. Some examples of these operators are as follows:
  - **A**∨**B** (or): either event A occurs, or event B occurs, or both
  - **A**∧**B** (and): event A and event B happen
  - ¬**A** (negation): event A does not occur
  - **A**→**B** (material implication): if event A happens, then event B happens
  - **A**↔**B** (bi-conditional):event B happens if and only if event A happens

LTL formulas are created by combining these operators. An example of Pattern Query in this language would be ◆*((A∨D)→ ∘B$\mathscr{U}$C)*. According to this expression, B must occur immediately after A or D and should continue to occur at least until C. Focusing on the ADL case study, an example of query defined with this language would be ◆*((House-*

work∨Deskwork)$\mathcal{W}$*Movement→Sport)*. This query searches for people who do their housework or study/work when they are at home. When they leave the house, they sports.

The chain formed by events and operators that constitute a query is sent from the server to the smartphone as a string. Once a smartphone receives the query, it loads it into the pattern query resolver, which decodes it and offers a series of methods to the other components to access the query data. In this method, the social process mining component allows us to specify patterns in this language to be processed later in the smartphone, accordingly, the individual process mining component understands which pattern the user's model must contain. Nevertheless, the Pattern Query language can be replaced by any other language that allows for the identification of patterns in the models.

6. Validation methodology

This section presents the proposed validation methodology, so that researchers wanting to apply the proposal in different case studies can assess whether it suits their needs. The validation focuses on three main dimensions: *The size and quality of the models discovered*. The first affects the readability of models obtained, while the second ensures that new models preserve their quality. *The amount of data sent to the server*. Because this affects the amount of user information going out of the smartphone, amount of network traffic generated, and amount of information to be subsequently processed by the server, as well as *the execution time*, and because the same hardware, software, and algorithms in the server-side have been employed in all approaches and scenarios evaluated, this metric can help us assess how the FPM-based proposal improves the workload rates with respect to a classical process mining-based approach. Different metrics are considered for each of these dimensions, following a federated process mining approach and a non-federated server-based process mining approach:

- Model size:
  - -*Number of activities*: The number of activities, that is, nodes, in the model.
  - -*Number of arcs*: The number of arcs, that is, relations between nodes, without considering their frequency.
  - -*Sum. arc weights*: The sum of the weights of all arcs, that is, the sum of the frequencies of all relations between nodes.
- Model quality:
  - -*Log fitness* [5,6]: A well-known metric in process mining to evaluate the replayability of traces.
  - -*Precision* [5,6]: A well-known metric that determines whether a model is precise. A model is deemed when it does not allow paths that do not exist in the event log.
  - -*Generalization* [5,6]: A well-known metric that determines whether a model filters too-specific components that are not frequently executed in the processes, if not, the generalization is considered poor.
  - -*Simplicity* [5,6]: A well-known metric that determines whether a model's execution paths are clear, that is, a model is simple when the relation between the number of transactions and the number of activities is lower.
- Amount of data sent to the server:
  - -*Total size of individual logs*: The amount of information, in kilobytes (KB), sent from smartphones to the server, to be stored and processed using process mining, which corresponds to the sum of the size of each individual log with the user's traces.
  - -*Size of integrated log*: The size (in KB) of the log that integrates the traces of the different users into a single event log.
  - -*Total size of logs*: The sum of the size (in KB) of the individual logs and integrated log.
- Execution time:
  - -*Time needed to generate the integrated log*: The time, in seconds (s), necessary for the server to merge the information of the individual logs in an integrated log.
  - -*Time needed to generate a process mining integrated log model*: The time (s) necessary for the server to discover processes belonging to the above-mentioned integrated log.
  - -*Time needed to generate process mining individual models*: The time (s) that the server needs to execute process discovery in all individual event logs to generate individual models related to the individual behavior of each user.
  - -*Average time to generate process mining individual models*: The average time (s) that the server needs to execute process discovery in each individual event log.

By evaluating and comparing these parameters in both approaches, it is possible to determine whether the proposed tool yielded processes of similar quality and smaller size while reducing space consumption and execution times. To ensure that the analysis was rigorous, a well-defined procedure was followed during validation.

Step 1: Define scenarios. The first step of the validation process is to define scenarios where social workflows are of interest. This is highly dependent on the case study. For example, in our case study, we defined 30 different scenarios, each associated with a different real situation. Moreover, the SOW was analyzed to identify people with a specific behavior, performing certain actions in a certain order during their daily routine.

Step 2: Define queries for the SOWCompact approach. To analyze these scenarios with a non-federated process mining approach, it is necessary to obtain all user data, generate a subsequent process model, and interpret the results obtained from the model. Because all scenarios considered belong to the same case study, the resulting model is the same in all scenarios. However, it can be assumed that the complexity of the model will be greater when the number of users and/or traces is high. This is owing to a highly probable increased heterogeneity of the integrated data.

The situation changes when using a federated process mining approach. In this case, an increase in users and/or traces will not automatically cause an increase in the complexity of the model. Because of the initial filtering on the users' devices, the resulting model is generated only on the SOW of people that meet certain behavior of interest for a scenario.

Once the scenarios are defined, a query that represents a particular behavior in each scenario must be defined to filter users and traces using the SOWCompact approach.

Step 3. Define the environment. The next step is to define the tools to be employed in each of the two approaches.

For the SOWCompact approach, the environment is composed of the tools described in Section 5. The PM4PY tool and heuristic miner algorithm [47] were employed on the server side. To compare the results of both approaches without them being influenced by the algorithm or process mining tool employed, we employed the same methods in the traditional non-federated process mining approach. However, other algorithms and process mining tools can be employed.

Our proposal offers a new application method for process mining tasks, not a new process mining algorithm for the discovery of processes. Therefore, it can be employed along with any classic or new process discovery algorithms.

Step 4. Setup the environment. After defining the environment, it is necessary to deploy it. The environment should be deployed on the same hardware in both approaches, and under the same conditions, for example, operating systems processes, other programs running background tasks, etc.

Using the source code available in the repositories linked in Section 5, the environment is set up as follows:

- *Social Process Mining:* The code in the repository must be downloaded and executed with any Python 3 distribution in a server.
- *Individual Process Mining:* The code in the repository must be downloaded and included as a module in any Android application, the following instructions on the repository. It is necessary to indicate the direction in which the component of social process mining is deployed.

Step 5. Interpretation of the results. The last step is the interpretation of the results obtained using both approaches in the case study and scenarios evaluated. Similar to step 1, this interpretation is highly dependent on the specific case study and should be adapted to the analyzed data. An example of appropriately analyzing the results in our case study is presented later.

Evaluation of the proposal on any case study and with any scenarios is possible if these steps are followed, allowing researchers to test the FPM in different contexts.

6.1. Case study: analysis of activity daily living (ADL) events

The case study selected for this study applies SOWCompact to mining social workflows on activity daily living (ADL).

A case study in the ADL domain was chosen because the events detected represent the day-to-day actions of users, hence, they contain high levels of variability and/or noise. However, despite this variability, there are always actions associated with user habits that are performed mostly in the same manner and order, that is, following the same process. By choosing this case study, the proposal faces the issues that make actual process mining techniques inappropriate for social workflows. Therefore, if the proposal performs correctly in this case study, it can be used for any other case study with less variable data and less noise. For example, the analysis of the process followed by users in their interactions with IoT devices or the process they follow when shopping through an app on their smartphones, etc.

Specifically, we used in this case study the dataset presented by Sztyler et al. [43] because it was generated with data from real users and it is a widely used and referenced dataset [44,39].

It contains ADL data generated by seven different real individuals, all males around 23 years of age. These data are presented as a set of event logs, one per individual, available in a public repository[6]. Each event log stores one trace for each user's day, including the processes the user has followed in his daily activities that day. The time frames of the user activities that are collected in each log are different, spanning from two days for the shortest and sixteen days for the longest. On average, the event logs captured seven users' activities for approximately ten days. They include twelve different daily activities that are common to most people's routines: *house work*, *meal preparation*, *eating and drinking*, *personal grooming*, *desk work*, *socializing*, *shopping*, *sports*, *movement*, *transportation*, *relaxing*, and *sleeping*. For each activity that is performed, an event is generated in the trace when the activity is completed, with the name of the activity that has just been completed.

The 30 different scenarios mentioned before were generated using this dataset. We detail five examples below:

- **Scenario 1:** The manager of a supermarket chain is interested in including a pre-cooked food section in their supermarkets. To do this, they need to know who would be interested in this kind of product. For example, determining if customers who usually go shopping every day before preparing a meal are usually people with little time to spare throughout the day.
- **Scenario 2:** A health science group is conducting research on the lifestyle of people who do not participate in sports. They are interested in finding out what the habits of these people are.

[6] https://sensor.informatik.uni-mannheim.de/#dataset_dailylog

- **Scenario 3:** A healthy habit recommended by health experts is not to park the car near one's home or workplace. Subsequently, the person must walk some distance when going to and leaving the car. It is necessary to analyze whether people who follow this recommendation also follow other healthy habits in their daily routines.
- **Scenario 4:** A local council is considering placing a new taxi stand in one of the local leisure areas to prevent people who meet their friends for a drink from taking their own car. To find out if this makes sense, they want to know if this is a frequent behavior among people in their locality.
- **Scenario 5:** A chain of fast-food restaurants wants to create a new menu for people who follow a healthy lifestyle, with promotions for those group visits. Accordingly, the chain wants to know the habits of those customers who usually go there in groups.

For each of these five scenarios, we established a query as follows:

- **Query Scenario 1 (**◆*(Shopping*→ ∘*Mealpreparation)***)**
- **Query Scenario 2 (**◆*(¬Sport)***)**
- **Query Scenario 3 (**◆*(Movement*→*Transportation)***)**
- **Query Scenario 4 (**◆*(Socializing*→ ∘*EatingDrinking*→*Transportation)***)**
- **Query Scenario 5 (**◆*(¬EatingDrinking*→ ∘¬*Socializing)***)**

The formulas used in these different scenarios all seek to represent behaviors that occur at some point in time. Therefore, there is a ◆ operator encompassing the rest of the formula, which represents the behavior sought. As detailed above, the LTL syntax used in the pattern query language supports these and other time-related scenarios.

7. Validation results

In this section we present the results of applying SOWCompact to the ADL case study following the methodology presented in the previous section. For brevity, only the results of the previously mentioned five scenarios are discussed here; the results obtained for the remaining scenarios have been submitted as a Supplementary material.

These, as well as rest of the queries for the 30 scenarios used to validate the proposal, can be found in the supplementary material, including a brief description of each scenario, in the document named *Scenarios and Queries*. These scenarios contemplate partial and total overlapping situations between different queries. The results obtained during the validation of these scenarios regarding different parameters are also included in the supplementary material.

The results mentioned in this section were obtained using the following hardware:

- The individual process mining component (only for SOWCompact) was deployed on Redmi Note 7 smartphones with Android 9, 4 GB of RAM, and a Snapdragon octa-core processor working at 2.2 GHz and OnePlus Nord smartphones with Android 10, 12 GB of RAM, and a Snapdragon octa-core processor working at 2.4 Ghz.
- The server component (in the traditional, non-federated process mining approach and SOWCompact) was deployed on a laptop running Windows 10 with 16 GB of RAM and an Intel Core i7-8550U processor with base and turbo frequencies at 1.8 GHz and 4.0 GHz, equipped with NVMe SSD technology for storage.

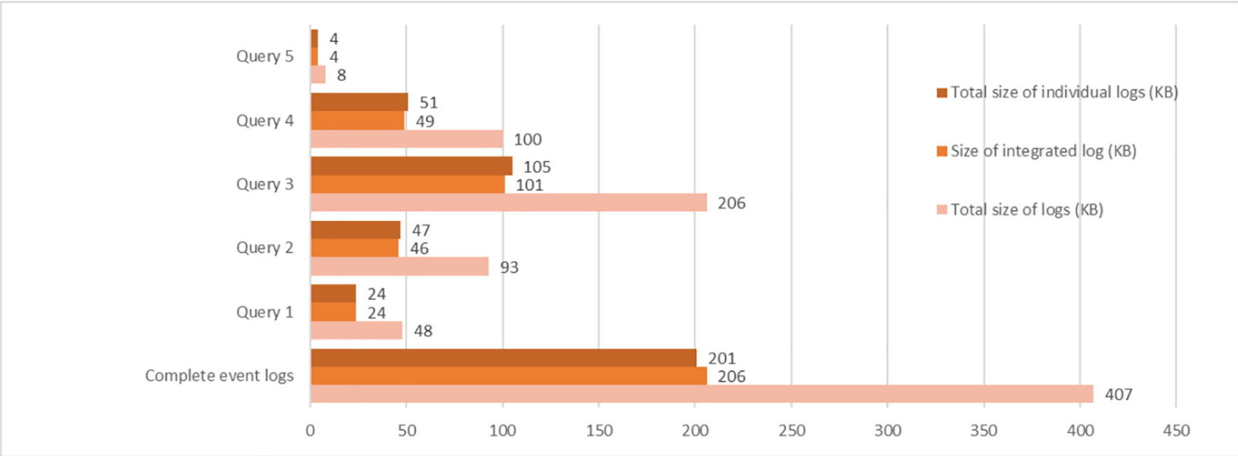
7.1. Data amount and computational load evaluation

We present an assessment of the amount of data sent to the server and the execution time on the server. The analysis of the validation results obtained in this subsection supports our main claim, that is, that we can generate more compact/smaller models without a loss of quality.

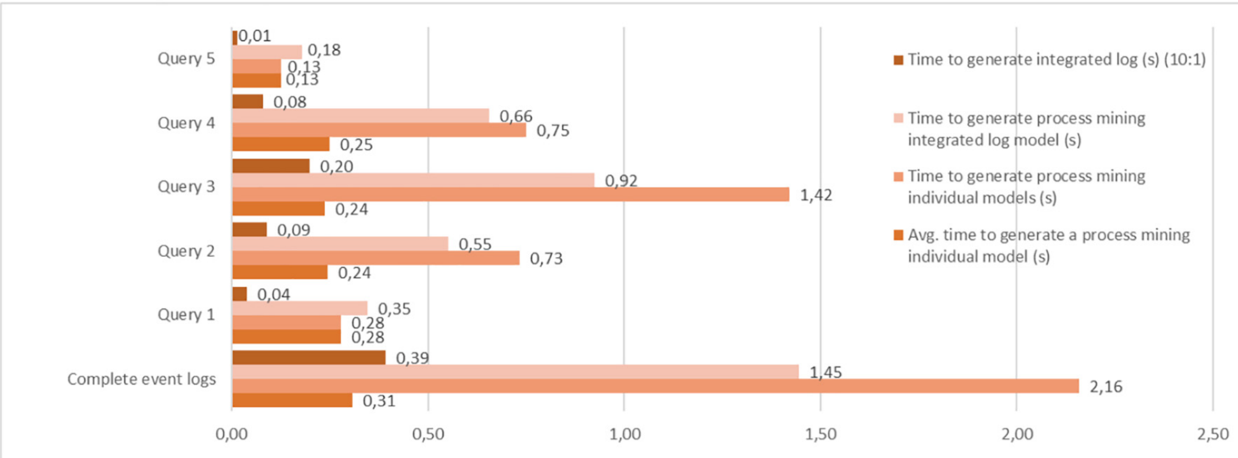
Fig. 5 shows the comparison between the results from the non-federated (*complete event log* values) and SOWCompact approach (*Query 1–5* values), both regarding the amount of data transferred from the users to the server (Fig. 5a) and execution time on the server (Fig. 5b). This comparison is made by measuring different parameters for each approach, and, as will be discussed later, demonstrates the optimization performed by the FPM approach on both data size and computational load for every scenarios. Each of these parameters was selected to cover some of the phases of the workflow described at the beginning of the validation for each of the two approaches (federated and non-federated).

On the one hand, the amount of data has been evaluated in terms of the *total size of the individual logs* sent to the server (full logs in the case of non-federated process mining and filtered logs in the case of SOWCompact), the size of the log generated in the server when the traces of these individual logs are integrated (*size of the integrated log*), and the size of all logs (individuals and integrated) in the server (*total size of logs*).

On the other hand, the computational load was evaluated in terms of the time required to process these data. Specifically, the time required to generate the integrated log in the server (*time to generate an integrated log* with 10:1 scale), time required to generate the process mining model with the integrated log (*time to generate process mining integrated log model*), and total and average time to generate models of individual logs in the server (*time to generate process mining individual mod-*



(a) Amount of data.



(b) Execution time.

Fig. 5. Evaluation of the amount of data and computational load.

els and *Avg. times to generate process mining individual models*, respectively); if this was necessary in the case study in which SOWCompact was applied. The reductions in these times translate into a reduced computational load on the server.

In the case of the non-federated approach, the results are the same for all scenarios evaluated because the users send their complete logs in all cases, regardless of the behavior pattern under consideration. This implies that the same amount of data is sent to the server and same computational load is incurred to process them in all scenarios. Therefore, the results of this approach are shown only once, under *complete event logs*. In the case of the SOWCompact approach, the results for each scenario are different, depending on how restrictive the query is or how common the behavior is. Therefore, the results for each of these scenarios are presented separately. The same applies to the evaluation of the quality and size of the models.

In the bar charts presented in Fig. 5, observe how the amount of data sent to the server is reduced (*Size total of individual logs* Fig. 5a) in all scenarios with the use of SOWCompact. This is because only the data that complies with the required pattern are sent. Therefore, filtering the amount of data sent to the server reduces data consumption on the users' smartphones, as well as the total size of logs and storage needs of the server. Likewise, the computational needs for processing these logs decrease proportionally, as depicted in Fig. 5b. This translates into a reduction in the number of resources required to compute the SOW models.

The percentage by which the amount of data is reduced depends on the frequency of a pattern. If it is a pattern that many users meet or users perform very often, it will result in more traces. Therefore, the size of the sent data will be closer to the size of the complete event logs. On average, for the five queries under consideration, the amount of data sent to the server is reduced to 23% of its original value, that is, from 201 KB to 24, 47, 105, 51, and 4 KB for Query 1–5, respectively. Moreover, the time necessary to generate the integrated log and its process mining model is reduced to 22% and 37% of their original values, that is, from 39.18 ms to 3.96, 8.92, 19.84, 7.93, and 1.48 ms and 1.44 s to 0.34, 0.55, 0.92, 0.65, and 0.17 s, respectively.

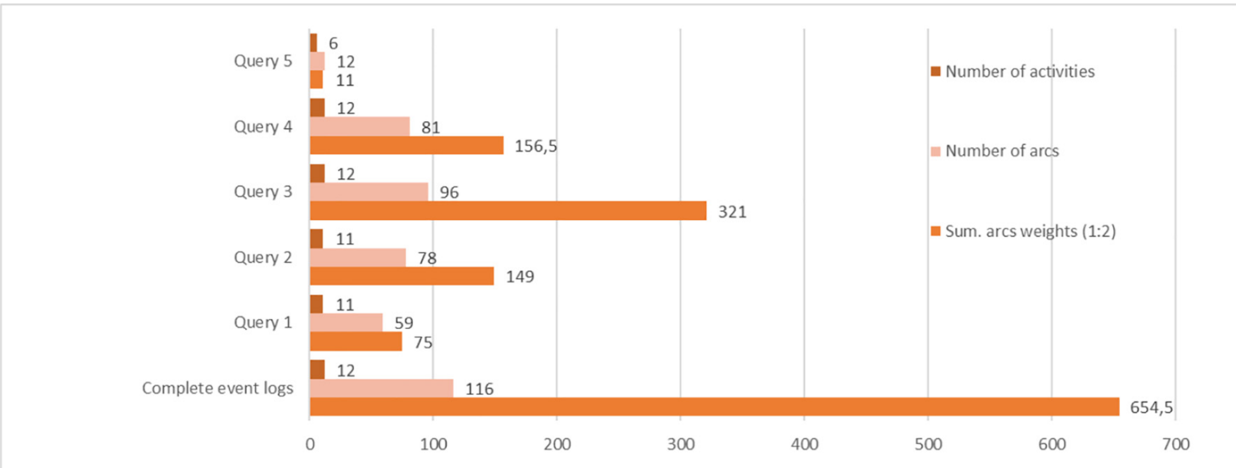
Therefore, it can be concluded that SOWCompact improves the amount of data that needs to be sent to the server and computational load required to process them compared to the use of server-based architectures; as was expected because of the federated nature of the proposal.

7.2. Evaluation of the models

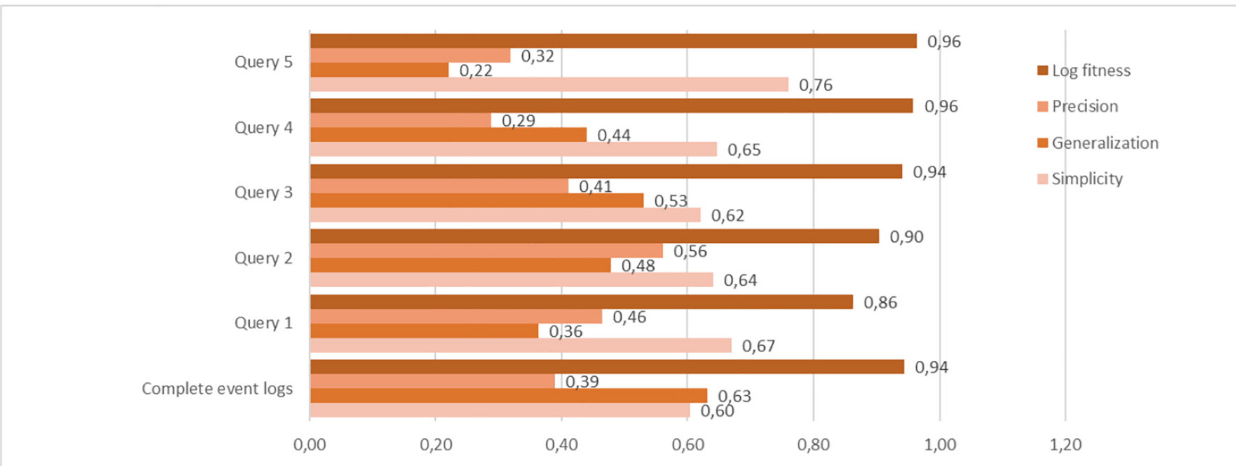
Even though the benefits in terms of computing requirements offered by SOWCompact are very significant, its main advantage comes from the fact that it allows for lighter process models. In this respect, the quality and size of the models discovered by SOWCompact were evaluated against those discovered using a traditional non-federated process mining technique. Four parameters were used to compare quality: *fitness, precision, generalization,* and *simplicity*. These parameters are widely used to measure the quality of process-mining models. Additional parameters such as number of activities, number of arcs, and sum of the weights of the arcs were included to evaluate model sizes. The visual representations of these models are included as heuristic nets corresponding to the models of different SOWs. This provides a graphic representation of the differences between the models generated by each approach. The full results of this validation, including more quality parameters and visual representation of each model, can be found in the supplementary material. For brevity, only the more relevant parameters are discussed.

7.2.1. Size of the models

The first three parameters that are evaluated are those referring to the size of the generated model. The results of these parameters are presented in Fig. 6a, comparing the server-based (*complete event log* value) and SOWCompact approaches. The values of these parameters are represented by the *number of activities*, *number of arcs* and *sum of arc weights* bars. These



(a) Size of the models.



(b) Quality of the models.

Fig. 6. Evaluation of the models.

values were obtained from the models generated using the PM4PY tool. The weights of the arcs are obtained from the heuristic net generated by the heuristic miner algorithm, which indicates how many times that the transition between the two activities has occurred (in the direction indicated by the transition).

7.2.2. Quality of the models

The remaining evaluated parameters were those referring to the quality of the generated model. These values were obtained using the PM4PY tool as well. The first of these parameters is *fitness*. The PM4PY tool divides into three different values: 1) *Percentage fit traces*, which indicate what percentage of the log traces are perfectly trained according to the model. 2) *Average fitness trace*, which indicates how well the model represents the behavior in the traces (with values between 0 and 1, with 1 being a perfect representation). 3) *Log fitness*, which offers a metric based on the two previous ones (1 when the traces are perfectly fitting). For all measurements, the values of *log fitness* and *average trace fitness* were similar.

The next parameter evaluated is *precision*. PM4PY used a proposal called *ETConformance* [31] to measure the precision. Another parameter evaluated was *generalization*. PM4PY's implementation of *generalization* is based on the work of Buijs et al. [6]. The last commonly used parameter evaluation parameter regarding process mining models is *simplicity*. PM4PY uses this idea to implement its "inverse arc degree" formula for simplicity. The results of these three parameters and *log fitness*, including a comparison of the two approaches, are presented in Fig. 6b.

In addition to the parameters discussed here, other quality parameters are included in the supplementary material. The value of *metrics average weights* is calculated based on the value of the last parameters (*fitness, precision, generalization*, and *simplicity*). This value indicates the overall quality of the model based on the above-mentioned characteristics. In addition, the parameter *fscore* is included, which is calculated based on the accuracy of the fitting traces and accuracy of the non-fitting traces.

7.2.3. Results of evaluating the models

In terms of size, the results obtained using different queries on SOWCompact demonstrate that smaller models can be obtained with a smaller number of arcs, lower arc weights, and fewer activities. This reduction in size is associated with an improvement in the *simplicity* metric. However, although some improvements are achieved in terms of simplicity, for all the scenarios presented, the simplicity increases by 11% on average, increasing from 0.60 in the classical non-FPM model to 0.67, 0.64, 0.62, 0.64, and 0.76 for the five FPM models. These results are less significant than those achieved regarding the model size. This is because, to increase simplicity, the number of arcs in relation to the number of activities must be reduced. SOWCompact goes one step further and filters the arcs and activities, instead of only filtering arcs. For the scenarios presented, on average, the number of activities decreased to 87% of the total, from 12 to 11, 11, 12, 12, and 6 for the five queries discussed. Moreover, the number of arcs decreases to 56%, from 116 to 59, 78, 96, 81, and 12, and sum of the weight of the arcs decreases to 22%, from 1309 to 150, 298, 642, 313, and 22.

For the rest of the quality parameters, the results are similar to those obtained for simplicity. The models generated with the federated process mining approach are mostly similar to the ones generated with a non-federated solution. However, they improve, the quality of the models generated in some cases.

8. Discussion

To discuss whether the SOWCompact proposal is substantially helpful for process mining, we proceed based on the the results obtained in the validation, which are as expected. Moreover, our hypothesis regarding the complexity of interpreting the models generated by the two different approaches has been corroborated. In addition, we have discussed how the benefits of the proposal are linked to the query used to filter the event logs. If a more restrictive query, or one that represents a less frequent behavior, namely, scenario 1, is used, simpler models are obtained with less data sent and computational loads. When more generic queries or queries that represent usual behavior are used, namely, scenario 3, benefits are still observed but on a smaller scale.

This validation was subjected to a robustness check to verify that there are no assumptions that might affect its results when the proposal is applied to a real-world environment. The robustness of the test cases, demonstrating the correct operation of the model in the face of erroneous inputs or stress situations was also tested. For the first type of situation, erroneous inputs were defined as incorrectly formatted queries, which depends on the analyst who defines the queries, or an event log generated in an incorrect format in one of the mobile devices, that is, XES format. In either case, the proposal handled these situations without crashes. In the first case, the data were not analyzed because the pattern of interest could not be interpreted. In the second case, the event log data in the wrong format were discarded. Regarding stress situations, these have not been validated beyond the seven users' devices. However, it has been proven that the system reacts to situations involving many synchronous queries. Specifically, it has been proven that the system works when 1–30 queries from the validation scenarios are performed simultaneously. No limits above the number of queries were tested.

After commenting on the robustness of the validation performed, we also want to note that this section is not intended to discuss the results offered by the algorithm employed to generate the SOW models. This work does not intend to compare the results of using different process mining algorithms because SOWCompact and federated process mining are generally ready to incorporate any alternative algorithm. Therefore, discussions regarding the robustness of individual models generated by the Alpha algorithm or social models generated by the heuristic miner are not considered here. The metrics depend on the algorithm employed [27]. Any other algorithm can be applied in our proposal by replacing the algorithms we have used. Instead, our discussion focuses on presenting the benefits, limitations, and applications of the proposed method, as well as defining its contributions to the field of process mining.

By using SOWCompact it was possible to create simpler models that contained the requested pattern, discarding all the other traces where this pattern was not present. This is achieved by carrying out two process mining phases: first an individual phase, and then a second one on the traces filtered. Filtering out not only the users that comply with a pattern in their individual model, but also their traces, to select only those that contain the pattern sought, means that the users' behaviors that do not comply with this pattern are also discarded. For example, in the case study of this paper, if the aim is to study the users' routines when they take part in sports, the traces that represent routines without sports would be discarded, eliminating their noise from the resulting model.

Producing a smaller model, but with the same quality (as demonstrated in the validation) and still containing the behavior of interest, helps improve the rest of the process mining tasks. Therefore, this proposal should not be considered a different tool for process mining, but as a novel method to improve the results yielded by other process mining tools.

A clear contribution of this method to process mining is the discovery of more readable models (see Figs. 1 and 2) for a visual comparison of models generated during validation with a classical non-federated approach and SOWCompact, respectively. The generated graphical model contained only relevant information about the social group of interest. Information that only adds noise and complicates the visualization of the model was excluded. This makes it easier for analysts to read the behavior represented in the model.

However, its contribution was not limited to this. In real applications, it is probable that even the model obtained using this method will remain complex for visual analysis. Nowadays, tools such as frequent pattern mining help to filter out the most erratic or less accurate behaviors from models. Using the proposed federated process mining as a method to apply these tools can help to improve their results, filtering the traces that are not of interest and looking for frequent patterns on the traces that contain a behavior of interest.

Thanks to all the above, the proposed method opens a new world of possibilities in the analysis of social workflows. First, this proposal enables the analysis of social workflows created from user action data that do not follow a well-defined process —not only in activity daily living (ADL) data, such as in the case study presented here, but also in other domains. For example, it can be used to analyze user interactions with smart devices (IoT). These types of actions can be chaotic and subject to user variability. When this variability is filtered at the individual level, integrating all data from users with different behavioral patterns, the model generated would not adequately represent any user or social group. However, if users were filtered to gather only data from those with a specific behavioral pattern, we would obtain a model that represents the social group formed by those users with a certain common behavior.

As a result, we can conclude that the limitations raised at the end of the related work have been satisfactorily addressed by the proposal: it allows both filtering the users that comply with a behavior of interest and those that do not; it takes advantage of the computational power of smartphones for this purpose, and yields better models—models that take into account the type of improvement that was intended.

However, even accepting the contribution of federated process mining makes to current process mining and its tools, the use of the proposed architecture can still be questioned. In this architecture, various distributed and connected components are needed, as well as the development of process mining tools for smartphones, which, to the best of our knowledge, are not yet widespread. An alternative hypothetical architecture could be proposed, where the same process is carried out in two phases, but on the server instead.

In this alternative version, users would have to send all traces to the server for filtering and processing. However, even without considering aspects such as privacy and other advantages of maintaining the user's virtual representations on their own devices, this would eliminate the improvements of our proposal in terms of the amount of data sent to the server and the server's computational load.

Although with the amount of data in the case study under consideration these kinds of optimizations might not seem efficient, it is important to remember that this case study only contained data from seven users, collected over an average of 10 days. However, for a larger case study, improvements obtained with this system are necessary. For example, it can be supposed that the described case study contained data from 100 million users instead of seven. This number of users, although high, could correspond to that of a social network (where the analysis of SOWs is particularly interesting) with several users below those in the Top 15 of the *Digital 2020: Global Digital Overview*[7]. Sending the logs of these 100 million users to the server would mean sending 2738 TB of data, that is, assuming that the logs were still for just ten days. If we assume that the proportion of users that comply with the pattern and the frequency with which they perform sequences of activities that comply with this pattern are maintained, we can extrapolate the percentages of improvement. In this case, if this architecture is used, instead of 2738 TB only 629 GB, 328 GB, 1423 GB, 684 GB and 54 GB would be sent for each of the five discussed scenarios. If, in addition to increasing the number of users, the time they interacted with the app that generated the data also increased, the size of the event logs would grow even more. Therefore, a distributed architecture similar to that in our proposal has direct repercussions and advantages, both for users and for those conducting process mining.

[7] https://datareportal.com/reports/digital-2020-global-digital-overview

Given the type of advantages offered by Federated Process Mining and in light of the above example, notice that federated process mining, although applicable to any type of scenario, is particularly suited for scenarios with large amounts of data. Scenarios where there are numerous different users presenting different behaviors, integrating all the users' data in the same model would result in a totally random and chaotic model, from which it would be impossible to extract knowledge.

Finally, it is necessary to keep in mind that, during the validation, some aspects of the design of the solution were noticed that are still subject to discussion. For example, in the proposed solution, every time a query is launched, users will send all the traces that comply with the required pattern, independently of whether that query had been previously executed and part of those traces had already been sent. Implementing a mechanism that allows tagging a trace if it has already been sent, to avoid resending it, would help further reduce the amount of data sent to the server (if the same query is repeated periodically).

9. Conclusions and future research directions

The aim of this study is to address the problems inherent to process mining over SOWs on a server, such as the variability of integrated traces and the large storage and computing requirements for the server. For this purpose SOWCompact, a federated process mining approach, is proposed. In SOWCompact the process mining of SOWs is divided into two stages: first one mining on the users' individual data, and a second one mining on the SOW of the users that meet a certain behavior of interest. Considering that smartphones are the best way to obtain a virtual representation of the user and those that are connected to all their services, these devices should collect the user data and perform the individual process mining stage.

Thus, the performance of the server is optimized, reducing both the need for data transfer and the computational load of the server. It also achieves more compact models, which are easier to interpret visually and offer less noise, by reducing the variability in the traces that are integrated with those existing between people with similar behavioral patterns.

To assess the validity of the proposed approach, a federated process mining tool, SOWCompact, was implemented and applied to a case study related to process mining of activities of daily living (ADL) data. The results are demonstrated as a comparison between a classic, server-based approach and our proposed method.

Based on the data obtained in the validation, we suggest that by using the federated process mining tool a clear improvement is achieved in terms of computing time and the amount of data sent to the server. This improvement differs according to how often the users meet the behavior of interest. It has also been verified that the federated approach produces models of the same quality as in the pure server approach, but is more compact, enabling a better visual interpretation of the data. This is based on the fact that the traces have been filtered using one of the simplest algorithms available, the Alpha algorithm, and that the server uses an algorithm capable of filtering by itself, the heuristic miner algorithm. This can be considered the worst-case scenario for FPM, while the best would be the opposite—a good filtering algorithm on the mobile device and a simpler algorithm on the server. This scenario was chosen to demonstrate that, even in the worst-case scenario, the proposal achieves its goal. Therefore, no other process-discovery algorithms were tested. The number of classic process discovery algorithms and new proposals, such as frequent pattern mining or clustering, is so large that the entire spectrum can never be covered. Therefore, considering the worst-case results as a reference is considered a good benchmark.

Moreover, the benefits obtained by this proposal could be further improved by including frequent pattern mining. This would produce models that are better at eliminating the noise of less frequent actions. In this way, models with better *generalization* and greater *simplicity* are obtained. This is one of the future lines of work for our proposal.

Additionally, our proposal opens new possibilities for the use of process mining for software development. First, our proposal can be used to manually and visually analyze data in a social workflow of users within a specific social group, as current process mining techniques and methods already do. However, it also opens the door to creating new automatic systems capable of making decisions, modifying the behavior of the system, or adapting to new situations, based on the information provided by federated process mining. The creation of tools that ensure an easy integration of federated process mining into such systems is one of many possible future research directions.

As additional future lines of work, a mechanism would be needed to update the individual models without regenerating them by including all user traces each time the event log is updated. For instance, incremental process mining allows updating of the model without generating a new one with all traces. Finally, future work should also include checking the improvements of federated process mining if a more intelligent algorithm of process mining in the individual process mining component is applied. In addition, for the actual validation it would be interesting to add an assessment of the energy footprint of the individual mining phase on smartphones.

CRediT authorship contribution statement

Javier Rojo: Writing - original draft, Writing - review & editing, Investigation, Software, Validation, Visualization, Formal analysis. **Jose Garcia-Alonso:** Validation, Methodology, Visualization, Writing - review & editing, Formal analysis, Funding acquisition, Project administration. **Javier Berrocal:** Validation, Funding acquisition. **Juan Hernández:** Methodology, Supervision. **Juan Manuel Murillo:** Conceptualization, Writing - review & editing, Funding acquisition, Supervision, Project administration. **Carlos Canal:** Conceptualization, Writing - review & editing, Funding acquisition, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014–2020), RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), and UMA18-FEDERJA-180 (Junta de Andalucía/ATech/FEDER), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

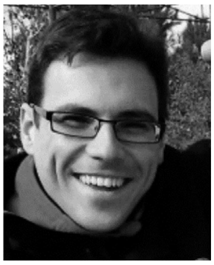
References

[1] W.M.P. van der Aalst, Process discovery: An introduction. In Process Mining: Discovery, Conformance and Enhancement of Business Processes (pp. 125–156). Berlin, Heidelberg: Springer, Berlin Heidelberg, 2011.https://doi.org/10.1007/978-3-642-19345-3_5..
[2] S. Aleem, L.F. Capretz, F. Ahmed, Business Process Mining Approaches: A Relative Comparison, 2015, arXiv:1507.05654..
[3] M.L. Bernardi, M. Cimitile, F. Martinelli, F. Mercaldo, A fuzzy-based process mining approach for dynamic malware detection, in: In 2017 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), 2017, pp. 1–8, https://doi.org/10.1109/FUZZ-IEEE.2017.8015490.
[4] J. Berrocal, J. Garcia-Alonso, C. Vicente-Chicote, J. Hernández, T. Mikkonen, C. Canal, J.M. Murillo, Early analysis of resource consumption patterns in mobile applications, Pervasive Mobile Comput. 35 (2017) 32–50.
[5] J.C. Buijs, B.F. Van Dongen, W.M. van Der Aalst, On the role of fitness, precision, generalization and simplicity in process discovery, in: OTM Confederated International Conferences On the Move to Meaningful Internet Systems, Springer, 2012, pp. 305–322.
[6] J.C.A.M. Buijs, B.F. van Dongen, W.M.P. van der Aalst, Quality dimensions in process discovery: The importance of fitness, precision, generalization and simplicity, Int. J. Cooperative Inf. Syst. 23 (2014), https://doi.org/10.1142/S0218843014400012.
[7] A. Burattin, F.M. Maggi, A. Sperduti, Conformance Checking Based on Multi-Perspective Declarative Process Models, Expert Syst. Appl. 65 (2015) 194–211, https://doi.org/10.1016/j.eswa.2016.08.040, arXiv:1503.04957.
[8] D. Chapela-Campa, M. Mucientes, M. Lama, Mining frequent patterns in process models, Inf. Sci. 472 (2019) 235–257, https://doi.org/10.1016/j.ins.2018.09.011.
[9] C. Charron, J. Favier, C. Li, Social computing: How networks erode institutional power, and what to do about it. Forrester Customer Report, 2006..
[10] R. Cirne, C. Melquiades, R. Leite, E. Leijden, A. MacIel, F.B.D.L. Neto, Data Mining for Process Modeling: A Clustered Process Discovery Approach. In Proceedings of the 2020 Federated Conference on Computer Science and Information Systems, FedCSIS 2020, 2020, pp. 587–590. Institute of Electrical and Electronics Engineers Inc. 10.15439/2020F95..
[11] A.A. De Medeiros, B.F. van Dongen, W.M. Van der Aalst, A. Weijters, Process mining: Extending the α-algorithm to mine short loops, 2004..
[12] A.K. De Medeiros, B.F. Van Dongen, W.M. Van Der Aalst, A.J. Weijters, Process mining for ubiquitous mobile systems: An overview and a concrete algorithm, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 3272 (2004) 151–165, https://doi.org/10.1007/978-3-540-30188-2_12.
[13] A.K.A. De Medeiros, A. Guzzo, G. Greco, W.M. Van Der Aalst, A.J. Weijters, B.F. Van Dongen, D. Saccà, Process mining based on clustering: A quest for precision, in: In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2007, pp. 17–29, https://doi.org/10.1007/978-3-540-78238-4_4, volume 4928 LNCS.
[14] O. Dogan, C. Fernandez-Llatas, B. Oztaysi, Process mining application for analysis of customer's different visits in a shopping mall. In Advances in Intelligent Systems and Computing (pp. 151–159). Springer Verlag, 2020, vol. 1029. DOI: 10.1007/978-3-030-23756-1_20..
[15] E.A. Emerson, Chapter 16 – temporal and modal logic. In J. VAN LEEUWEN (Ed.), Formal Models and Semantics Handbook of Theoretical Computer Science (pp. 995 – 1072). Amsterdam: Elsevier, 1990.https://doi.org/10.1016/B978-0-444-88074-1.50021-4..
[16] M.C. Gonzalez, C.A. Hidalgo, A.-L. Barabasi, Understanding individual human mobility patterns, Nature 453 (2008) 779–782, https://doi.org/10.1038/nature06958.
[17] S. Görg, R. Bergmann, Social workflows – Vision and potential study, Inform. Syst. 50 (2015) 1–19, https://doi.org/10.1016/j.is.2014.12.007.
[18] J. Guillén, J. Miranda, J. Berrocal, J. Garcia-Alonso, J.M. Murillo, C. Canal, People as a Service: A mobile-centric model for providing collective sociological profiles, IEEE Softw. 31 (2014) 48–53, https://doi.org/10.1109/MS.2013.140.
[19] C.W. Gunther, H.M.W. Verbeek, D. Dolech, A.Z. Eindhoven, C.W. Günther, E. Verbeek, XES-standard definition. Technical Report, 2014..
[20] E. Gupta, A.P. Esmita Gupta, Process mining a comparative study, Int. J. Adv. Res. Comput. Commun. Eng. 3 (2014) 2319–5940, https://doi.org/10.17148/ijarcce.
[21] D.C. Hay, Making data models readable, Inform. Syst. Manage. 15 (1998) 21–33, https://doi.org/10.1201/1078/43183.15.1.19980101/31099.4.
[22] I. Hwang, Y.J. Jang, Process mining to discover shoppers' pathways at a fashion retail store using a wifi-base indoor positioning system, IEEE Trans. Autom. Sci. Eng. 14 (2017) 1786–1792, https://doi.org/10.1109/TASE.2017.2692961.
[23] S. Jablonski, M. Röglinger, S. Schönig, K.M. Wyrtki, Multi-perspective clustering of process execution traces. Enterprise Modelling and Information Systems Architectures (EMISAJ) -, Int. J. Conceptual Modeling 14 (2019) 1–22, https://doi.org/10.18417/emisa.14.2.
[24] S. Katz, Assessing self-maintenance: activities of daily living, mobility, and instrumental activities of daily living, J. Am. Geriatr. Soc. (1983), https://doi.org/10.1111/j.1532-5415.1983.tb03391.x.
[25] S. Kim, D. Kim, Analyzing mobile application logs using process mining techniques: An application to online bookstores, ICIC Express Letters, Part B: Applications 9 (2018) 607–614, https://doi.org/10.24507/icicelb.09.06.607.
[26] S. Laso, M. Linaje, J. Garcia-Alonso, J.M. Murillo, J. Berrocal, Deployment of apis on android mobile devices and microcontrollers, in: In 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), 2020, pp. 1–3, https://doi.org/10.1109/PerComWorkshops48775.2020.9156208.
[27] S. Leemans, Robust process mining with guarantees. Ph.D. thesis Mathematics and Computer Science. Proefschrift, 2017..
[28] D. Loreti, F. Chesani, A. Ciampolini, P. Mello, A distributed approach to compliance monitoring of business process event streams, Future Gener. Comput. Syst. 82 (2018) 104–118, https://doi.org/10.1016/j.future.2017.12.043.
[29] I. Meddah, B. Khaled, Discovering Patterns using Process Mining, Int. J. Rough Sets Data Anal. 3 (2016) 21–31, https://doi.org/10.4018/ijrsda.2016100102.
[30] J. Miranda, N. Mäkitalo, J. Garcia-Alonso, J. Berrocal, T. Mikkonen, C. Canal, J.M. Murillo, From the internet of things to the internet of people, IEEE Internet Comput. 19 (2015) 40–47, https://doi.org/10.1109/MIC.2015.24.
[31] J. Muñoz-Gama, J. Carmona, A fresh look at precision in process conformance. In R. Hull, J. Mendling, & S. Tai (Eds.), Business Process Management (pp. 211–226). Berlin, Heidelberg: Springer, Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-15618-2_16..
[32] M. Ocaña, Á. Llamazares, P.A. Revenga, M.A. García-Garrido, N. Hernández, P. Álvarez, J. Fabra, D. Chapela-Campa, M. Mucientes, M. Lama, A. Bugarín, J. M. Alonso, Estimation of customer activity patterns in open malls by means of combining localization and process mining techniques. In Advances in

Physical Agents II: Proceedings of the 21st International Workshop of Physical Agents (WAF 2020) (p. 30). Springer Nature.https://doi.org/10.1007/978-3-030-62579-5_3..
[33] P. Pichler, B. Weber, S. Zugal, J. Pinggera, J. Mendling, H.A. Reijers, Imperative versus declarative process modeling languages: An empirical investigation. In Lecture Notes in Business Information Processing (pp. 383–394). Springer Verlag volume 99 LNBIP, 2012.https://doi.org/10.1007/978-3-642-28108-2_37..
[34] A. Polyvyanyy, C. Ouyang, A. Barros, W.M. van der Aalst, Process querying: Enabling business intelligence through query-based process-analytics, Decis. Support Syst. 100 (2017) 41–56, https://doi.org/10.1016/j.dss.2017.04.011.
[35] M. Russell, Mining the Social Web: Analyzing Data from Facebook, Twitter, LinkedIn, and Other Social Media Sites, O'Reilly Media, 2011.
[36] H. Schonenberg, B. Weber, B. van Dongen, W. van der Aalst, Supporting flexible processes through recommendations based on history, in: In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2008, pp. 51–66, https://doi.org/10.1007/978-3-540-85758-7-7, volume 5240 LNCS.
[37] S. Schönig, C. Di Ciccio, F.M. Maggi, J. Mendling, Discovery of multi-perspective declarative process models. In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) (pp. 87–103). Springer Verlag volume 9936 LNCS, 2016.https://doi.org/10.1007/978-3-319-46295-0_6..
[38] D. Schuler, Social computing, Commun. ACM 37 (1994), https://doi.org/10.1145/175222.175223, Social Computing: any type of computing application in which software serves as an intermediary or a focus for a social relation.
[39] P. Soffer, A. Hinze, A. Koschmider, H. Ziekow, C. Di Ciccio, B. Koldehofe, O. Kopp, A. Jacobsen, J. Sürmeli, W. Song, From event streams to process models and back: Challenges and opportunities, Inform. Syst. 81 (2019) 181–200.
[40] M. Song, C.W. Günther, W.M. Van Der Aalst, Trace clustering in process mining. In Lecture Notes in Business Information Processing (pp. 109–120), 2009. Springer Verlag volume 17 LNBIP. DOI: 10.1007/978-3-642-00328-8_11..
[41] R.A. Sutrisnowati, H. Bae, I.R. Pulshashi, A.D.A. Putra, W.A. Prastyabudi, S. Park, B. Joo, Y. Choi, BAB Framework: Process Mining on Cloud, Procedia Comput. Sci., 72, Elsevier B.V, 2015, pp. 453–460, https://doi.org/10.1016/j.procs.2015.12.126.
[42] T. Sztyler, J. Carmona, J. Völker, H. Stuckenschmidt, Self-tracking reloaded: Applying process mining to personalized health care from labeled sensor data. In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) (pp. 160–180). Springer Verlag volume 9930 LNCS, 2016.https://doi.org/10.1007/978-3-662-53401-4_8..
[43] T. Sztyler, J. Völker, J. Carmona, O. Meier, H. Stuckenschmidt, Discovery of personal processes from labeled sensor data - An application of process mining to personalized health care, in: CEUR Workshop Proceedings, 2015, pp. 31–46, CEUR-WS volume 1371.
[44] N. Tax, N. Sidorova, W.M. van der Aalst, Discovering more precise process models from event logs by filtering out chaotic activities, J. Intell. Inform. Syst. 52 (2019) 107–139.
[45] W.M. Van Der Aalst, M.H. Schonenberg, M. Song, Time prediction based on process mining, Inform. Syst. 36 (2011) 450–475, https://doi.org/10.1016/j.is.2010.09.001.
[46] F.-Y. Wang, K.M. Carley, D. Zeng, W. Mao, Social computing: From social informatics to social intelligence. IEEE Intelligent Systems, 22, 2007, 79–83. https://doi.org/10.1109/MIS.2007.41. Social Computing: Computational facilitation of social studies and human social dynamics as well as the design and use of information and communication technologies that consider social context..
[47] A. Weijters, W.M. van Der Aalst, A.A. De Medeiros, Process mining with the heuristics miner-algorithm. Technische Universiteit Eindhoven, Tech. Rep. WP 166 (2006) 1–34.
[48] J. Wen, M. Zhong, Z. Wang, Activity recognition with weighted frequent patterns mining in smart environments, Expert Syst. Appl. 42 (2015) 6423–6432, https://doi.org/10.1016/j.eswa.2015.04.020.
[49] A. Yassine, S. Singh, A. Alamri, Mining human activity patterns from smart home big data for health care applications, IEEE Access 5 (2017) 13131–13141, https://doi.org/10.1109/ACCESS.2017.2719921.
[50] K. Yongsiriwit, N.N. Chan, W. Gaaloul, Log-based process fragment querying to support process design. In Proceedings of the Annual Hawaii International Conference on System Sciences (pp. 4109–4119). IEEE Computer Society volume 2015-March, 2015.https://doi.org/10.1109/HICSS.2015.493..

Javier Rojo is a PhD student at the University of Extremadura. He has a predoctoral position at the same university, through a grant for the formation of university professors, from the Spanish Ministry of Science, Innovation and Universities. He obtained his MSc. in Computer Science at the University of Extremadura in 2021. His research interests include software engineering, eHealth, pervasive computing, mobile computing, and gerontechnology.

Jose Garcia-Alonso is an Associate Professor at the University of Extremadura and co-founder of Gloin, a software-consulting company and Health and Aging Tech, a eHealth company. He got his PhD on software engineering at the University of Extremadura in 2014. His research interests include software engineering, mobile computing, pervasive computing, eHealth, gerontechnology.



Javier Berrocal received the Ph.D. degree in computer science from the University of Extremadura, Spain, in 2014. In 2016, he obtained an Associate position at the University of Extremadura. His main research interests are mobile computing, context awareness, pervasive systems, crowd sensing, the Internet of Things, and fog computing. He is a cofounder of the company Gloin, which is a software-consulting company.

Juan Hernandez received the Ph.D. degree in Computer Science from the Technical University of Madrid, Spain, in 1995. He is currently a Full Professor at the University of Extremadura and the Head of the Quercus Software Engineering Group. His research interests include service-oriented computing, ambient intelligence, and model-driven development.

Juan Manuel Murillo is a co-founder of Gloin and a full professor at the University of Extremadura. His research interests include software architectures, mobile computing, and cloud computing. Murillo has a PhD in computer science from the University of Extremadura.

Carlos Canal is a full professor at the University of Malaga, Spain. His research interests include mobile and cloud development. Canal has a PhD in computer science from the University of Malaga. Contact him at carloscanal@uma.es.

Chapter 6

Blockchains' federation for enabling actor-centered data integration

Authors: *Javier Rojo, Juan Hernandez, Luca Foschini, Paolo Bellavista, Javier Berrocal, Juan M Murillo Rodriguez, José García-Alonso.*

Publication type: *Conference paper.*

Conference: *IEEE International Conference on Communications.*

Year of publication: *2022.*

DOI: *10.1109/ICC45855.2022.9838506*

2021 GGS Class (Rating): *2 (A).*

ICC 2022 - IEEE International Conference on Communications | 978-1-5386-8347-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICC45855.2022.9838506

Blockchains' federation for enabling actor-centered data integration

Javier Rojo*, Juan Hernandez*, Luca Foschini†, Paolo Bellavista†,
Javier Berrocal*, Juan M. Murillo Rodriguez* and José García-Alonso*
*Department of Computer Systems and Telematics Engineering, University of Extremadura, Spain.
†Dipartamento di Informatica-Scienza e Ingegneria, University of Bologna, Italy.
[javirojo, juanher, jberolm, juanmamu, jgaralo]@unex.es, [luca.foschini, paolo.bellavista]@unibo.it

***Abstract*—The pervasive presence of the Internet results in an increasing number of people and systems interacting with each other. However, since each system only captures its own representation of reality, the information of the involved actors is scattered and even duplicated. This scattering generates problems by itself since only a small fragmented vision of the actors' reality is available for each system. At the same time, the duplication of information in different systems can lead to inconsistencies that impede the correct integration of different systems. In this paper, we present an architecture based on the use of an upper blockchain in charge of federating a set of lower-level blockchains. This way, actor-centered data integration is achieved, offering a single, global vision of the dispersed information of each actor. This solution, called FedBlocks, relies on the blockchains' federation concept where all interconnected systems are communicated and can share authorized data of their actors, providing a benefit for these systems and for the actors themselves. The proposed implementation has been successfully tested integrating 5689 records from 50 different institutions, belonging to 1156 actors.**

***Index Terms*—Data integration, interoperability, permissioned blockchain, web services, computer architecture**

I. Introduction

The expansion of the Internet has driven society towards a connected world, offering a universe of services and connection possibilities. Every day, there are more services providing support around the same domain. One example of this is the health domain, where an increasing number of Internet of Medical Things (IoMT) manufacturers have arisen in the last few years [1]. In this scenario, companies have changed their strategies regarding their information systems, going from cloistered systems with very few controlled connections to the outside to systems with open doors through well-defined APIs to exchange information. With this change, the Internet has become a continuously growing repository of information about every reality in the world.

However, due to the way in which this communication between services has been conceived, the information of different systems is never integrated. Each of them stores an isolated copy of its actors' data, and only the minimum amount of information needed is exchanged with other services. This has led the Internet to suffer a level of data duplication never suspected before. Every time a person interacts with a service they leave personal data and this information tends to be duplicated in many services.

There are many problems that arise from this duplication and fragmentation, ranging from the impossibility of obtaining a joint vision of the data to the potential inconsistency between data that refer to the same reality. A clear example of this can be found in healthcare, where patients who interact with different health systems throughout their lives have their information, their Electronic Health Records (EHRs), split between different information systems [2]. This hinders the creation of the complete health history of the patient, their *Personal Health Trajectory* [3], which can lead to severe complications when trying to provide the best possible treatment to these patients.

One solution to deal with these problems is Blockchain. It promotes decentralization, sharing, and openness; guaranteeing traceability and security in the data. For that, it uses the ledger abstraction which models the shared unique record of the transactions between different systems, having each of them a connected copy of the blockchain. Therefore, a possible solution to the duplication and fragmentation problems could be a permissioned blockchain —only users with sufficient rights can read and write content— per actor. This way, each service can have a node of the blockchain and interact with it each time the actor is involved. Several industrial implementations for permissioned blockchain solutions [4] can be employed, like the Hyperledger project [5].

However, it seems unrealistic to believe that all services and companies involved can agree to share a single blockchain. This is one of the reasons why recent proposals focus on interoperability between multiple blockchains [6]–[12]. These proposals are mostly focused on technical aspects of interoperability, like throughput, and do not take into account data duplication or inconsistencies.

To address these problems, we propose the use of one main blockchain complemented by the individual, per actor, blockchains. These individual blockchains are used by the different systems through the main blockchain and contain a single and consistent version of the actor information. The main blockchain serves as an address directory, where any allowed service can find where an actor data is located while the individual blockchains can be linked with the information systems of the different services without having to change them. Thanks to this, the information of each actor is organized in a unique structure that is accessible for different services.

The rest of this paper has been structured as follows: Section II analyzes the literature available for blockchains interoperability. Section III formulates the concept of blockchains' federation and proposes an architecture and an implementation. Section IV details the validation of the implementation and the performance of its main blockchain. Finally, in Section V, the conclusions of this work and some future lines of research are exposed.

II. Motivations and Related Work

The need for distributed storage systems is a reality caused by the growing number of services people interact with during their lives [13]. The communication between these services to pool the information of a person must be allowed to provide the best service possible to the users in any domain [2].

Blockchain technology —used to create distributed storage systems and promote information exchange— is a perfect fit. Industrial solutions with this goal are BurstIQ[1], that enables information exchange on healthcare scenarios, SimplyVital Health[2] or MedicalChain[3] focused on patient information. These show that the use of blockchain to address problems such as interoperability between health systems and the sharing of patient data is not at all far-fetched. Works such as [14] analyze the potential of blockchain in these scenarios and define precisely these two usages as two of the future research goals. However, all these proposals offer full, integral information systems, requiring institutions and services to migrate their information from their actual information systems to the new one, something really difficult to conceive on a large scale.

Focusing on the use of Blockchain over existing information systems, making their data interoperable still requires the agreement between service providers and involved companies operating the blockchain in key aspects such as the different roles, trusted authorities, or smart contracts [15]. The difficulty of reaching these agreements grows as the number of parties involved increases, causing companies to mainly adopt blockchain for the implementation of their own systems as a useful way to record transactions between all their subsystems. There are actually few large-scale blockchain implementations and they are related to heavily regulated businesses such as banking [16].

Proposals promoting the interoperability between blockchains, like [8], where each one stores a part of the information, can be a solution. For example, Sidechains [10] have arisen as a method to interconnect several blockchains using another mainchain. This mainchain contains all its transactions and all transaction of its associated sidechains. This technology has been adopted by several public blockchains due to their high rate of transactions per unit of time. However, as far as the authors know, sidechains are not implemented by permissioned blockchain technologies, making them not suitable for solutions with private information.

[1]https://www.burstiq.com/
[2]https://www.f6s.com/simplyvitalhealth
[3]https://medicalchain.com/en/

Other proposals, like [11], discuss the concept of multichain, where a router blockchain is used to make interoperable a series of lower-level blockchains. However, this proposal is focused on inter-blockchain communication and increasing the throughput of operations over a single blockchain and provides no improvement for duplications or inconsistencies in the actors' information. Proposals such as Herlihy et al. also talk about the use of several independent blockchains, defining cross-chain deals [12]: a new computational abstraction for the structuralization of complex distributed exchanges in an adversarial environment. Wan et al. [9] define their own concept of Blockchain Federation, which enables the communication between multiple blockchains at the same level to meet the requirements of security, scalability, privacy, safety, and connectivity to enable trustable IoT.

Additionally, some works propose the use of different technologies to achieve interoperability between blockchains. Bellavista et al. [6] analyze the different types of interoperability available in the literature. However, their solution does not make use of an upper blockchain for the communication of lower-level blockchains. Instead, they use a gateway for transferring transactions between smart contracts of heterogeneous blockchains. Although this solution enables communication between blockchains, their proposal does not seek to avoid data duplication and inconsistencies. In the same way, Ghost et al. [7] also propose a decentralized gateway that allows interoperability between different private and public blockchains.

However, although these proposals also achieve the objective of communicating different blockchains, the use of an upper blockchain, instead of another type of technology to centralize the individual blockchains, provides an additional control mechanism to avoid undetected changes in the actor blockchains. Likewise, all the presented proposals achieve inter-blockchain communication and even increase the performance and security of operations over a single blockchain, but none of them is focused on reorganizing information or focus on eliminating duplicity or inconsistencies in one actor's information. Therefore, it is necessary to provide new ways of inter-blockchain communication that achieve this.

III. Blockchains' federation

In this work we propose a routing blockchain structure that, employed alongside an individual blockchain per actor, allows actor-centered data integration. The use of this blockchain—*main blockchain*—alongside the actors blockchains, blockchains' federation. In this section we provide an architecture for blockchains' federation and a reference implementation called FedBlocks.

A. Blockchains' federation architecture

The proposed architecture, showed in Figure 1, revolves around adding software components over existing information systems, without the need for services or institutions to replace their existing solutions. The unifying component of the architecture is the main blockchain, a permissioned blockchain

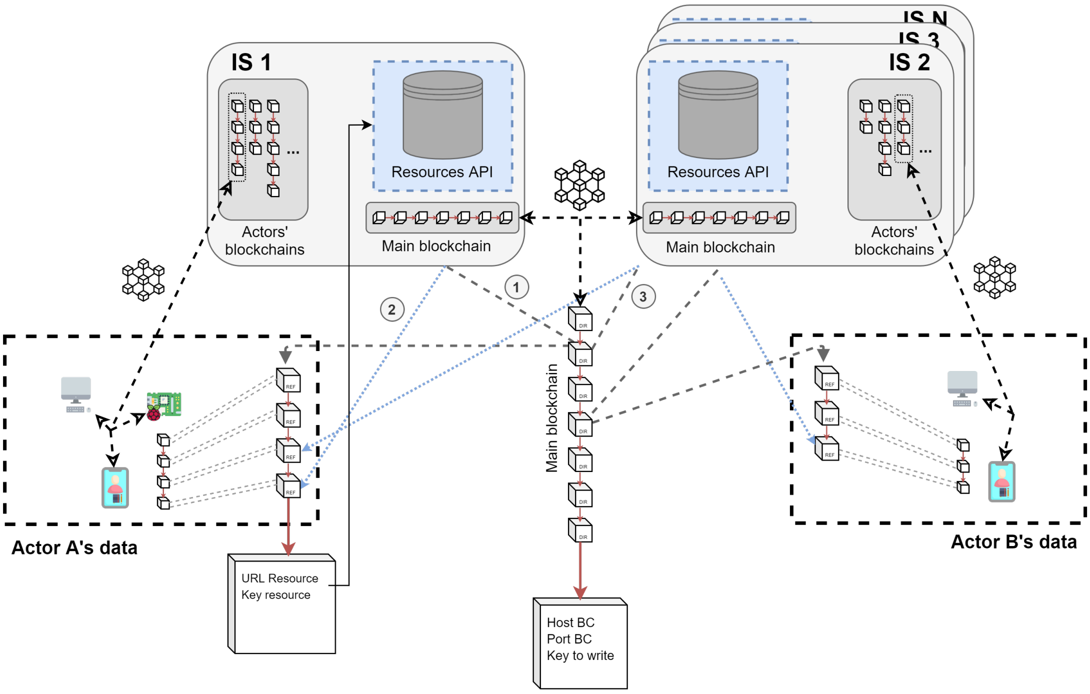


Fig. 1. Architecture based on blockchains' federation for actor-centered data integration.

shared by all the Information Systems (IS) that allows them to share their actors' information while maintaining complete control over their own systems. To this end, each IS has an individual permissioned blockchain for each of their actors and a Resources API to store the information that is too heavy to be directly stored in the blockchain. Each actor can also have a node of their own blockchain, which provides them with a unified access to all their information and empowers them to extract additional value from it.

Each IS has a node of the main blockchain that can be used to (1) locate where an actor's blockchain is deployed, and, (2) read or write to it. These operation can be similarly performed by IS that have no previous information of the actor. When this happens, instead of creating a new blockchain, the IS will (3) locate the actor blockchain through the main blockchain.

The actors' information is safely stored by each IS through their Resources APIs and the information is kept in the IS of the institution that generates it. To make it reachable, every time the data of an actor is modified through the Resources API, the operation is recorded as a new block. This block contains both the location where Resources API expose the data and the information that allows access to it.

To allow the integration and communication of data between different systems, each block of the main blockchain includes the deployment location of an actor's blockchain and how it can be accessed. Each actor have only one blockchain and which IS deploys each actor's blockchain must be decided by a common criteria between organizations—being this an easier to reach agreement than the use of shared information systems. If an actor does not want institutions to share their data, she will not have an actor's blockchain —without affecting the rest of the system.

However, since all the organizations have access to the main blockchain, they are communicated and the access to actors information is guaranteed. Using only one main blockchain, ensures that all institutions operate with the same actors' blockchains, mitigating information scattering. It also protects institutions from unwanted attacks, given the *state of truth* of blockchain. Additionally, if the location of an actor's blockchain changes, when an institution notifies it the rest will be aware, so they can keep interacting in the future.

B. Blockchains' federation model

Blockchains' federation refers to the usage of multiple blockchains for managing data following a two-level infrastructure. This way, several lower-level blockchains can be interconnected using another blockchain at the top which is in charge of nesting them and providing access to them.

The proposed system is composed of: {*actors, services, actors blockchains, main blockchain, information systems*} where there are from 1 to n copies of each of them.

The formal definition of blockchains' federations attends to a series of well-defined restrictions that must be complied with by any system applying it:

1) There will be only one main blockchain (MB) in the whole system.

$$\sum_{i=1}^{\inf} MB = 1 \tag{1}$$

TABLE I
LIST OF NOTATIONS

Variable	Meaning
S	Services sharing the data of their actors
A	Set of actors in the system
B	Blockchain nodes in the system
AB	Set of nodes actors blockchains
AB_a	Node of an actor blockchain
$AB(x)$	Set of nodes actor x blockchain
MB	Main blockchain
MB_a	Node of the main blockchain
$MB(x)$	Blocks of the main blockchain referring actor x

2) There will be from n to infinite main blockchain nodes (MB_a) in the system, where n is the number of services (S) sharing the data of their actors.

$$\sum_{i=1}^{\inf} MB_i \geq S \tag{2}$$

3) Each service sharing the data of its actors (A) must have from 1 to infinite main blockchain nodes.

$$\forall MB_a \epsilon MB : \sum MB_a > 1 \tag{3}$$

4) For an actor a, only at least one actor blockchain (AB) will exist in the whole system.

$$\forall a \epsilon A : \sum AB(a) = 1 \tag{4}$$

$$\begin{aligned} &\forall AB(i), AB(j) \epsilon AB, \forall i, j \epsilon A : \\ &!(AB(i) = AB(j) \wedge i \neq j) \end{aligned} \tag{5}$$

$$\begin{aligned} &\forall AB(i), AB(j) \epsilon AB, \forall i, j \epsilon A : i = j \\ &\implies AB(i) = AB(j) \end{aligned} \tag{6}$$

5) There will be at least one node of each actor blockchain

$$\forall a \epsilon A : \sum_{i=1}^{\inf} AB(a)_i \geq 1 \tag{7}$$

6) For every actor, there will be at least one block in the main blockchain that references it.

$$\forall a \epsilon A : \sum MB(a) \geq 1 \tag{8}$$

C. FedBlocks' Implementation

FedBlocks allows unified access to distributed data grouped by the actor. To allow this, it employs an architecture based on blockchains' federation and offers an API to facilitate the integration of this tool in any system. For the implementation of Fedblocks Hyperledger Iroha[4] was used. Iroha allows the deployment of permissioned blockchains and includes a service that allows working with the blockchains without needing a local copy. This service allows communication with an Iroha's blockchain node using gRPC. For this purpose, Iroha provides a series of APIs employed on FedBlocks to create a connector, allowing to use FedBlocks from software applications without a copy of the blockchain. The implementation of each of the components of the IS[5] and the FedBlocks connector[6] is discussed below.

Actors' blockchains. Implemented as an Iroha blockchain, it stores one transaction per block. This transaction represents a change in the actor's data. If that change is to add, modify or delete information, it is determined by the description of the transaction, so a registry of changes on the actor's information is available—improving the security of its health data since all accesses for that can be monitored [17].

Main blockchain. Also implemented with Iroha, it has a transaction for each actor present in an institution. In the description of this transaction, it is stored where the actor's blockchain is located, alongside the actor identifier. Adding a transaction to this blockchain must be done by the information system managers, after deploying the actor's blockchain.

FedBlocks connector. This component allows developers to easily use FedBlocks as a storage method. The connector can be integrated into any software application and it offers the series of operations that can be employed to add and retrieve information from a given actor. To use it, it is needed to connect to one of the nodes of the main blockchain or the blockchain's node of an actor.

FedBlocks connector REST API. For those developers who prefer to deploy the FedBlocks connection as a web service to which all their applications connect, a REST API is provided that offers the FedBlocks connector methods via HTTP requests.

Resources API. Responsible for storing the actor information. It offers an API where the information is sent to be stored and where it can be recovered later. When the API receives new information, it establishes an identifier and password, which is returned to the sender and that will be validated later when the information is to be retrieved.

To use FedBlocks, the deployment of blockchains in existing information systems is all that is needed. Using the Resources APIs is optional, as long as an alternative method of storing and referencing the information is provided. By using the Connector or its REST API, the development of actor-centered software for that system, reutilizing current applications or developing new ones, is achieved.

IV. FedBlocks' evaluation

To validate the proposal, an application using FedBlocks has been implemented. This application allows doctors from different institutions to access the data and add new records to patients of any institution subscribed to FedBlocks. This could be a first step towards using FedBlocks to integrate distributed EHRs whose information, despite being sensitive patient information, is useful to be shared among different

[4] https://github.com/hyperledger/iroha

[5] https://bitbucket.org/spilab/is_components

[6] https://bitbucket.org/spilab/fedblocks_connector_api

institutions. Global sharing of information such as allergies, blood group, or Covid-19 vaccination card of each citizen can be an example of the use of FedBlocks in healthcare. The implementation of the application is available in the Fedblocks' repository[7].

The evaluation has been divided into two phases. First, a conceptual evaluation and, second, a performance assessment. All tests performed and their values have been registered by the deployment of the FedBlocks architecture in the following environment:

- **Information Systems:** EC2 instances from Amazon Web Services with Ubuntu 18.04 LTS, 1 virtual core at 2.5GHz, and 1GB of memory.
- **Doctors computer:** a laptop with Windows 10, 16GB of RAM, an Intel Core i7-8550U at 1.8GHz base frequency and 4.0GHz turbo frequency, and NVMe SSD storage.

A. *Conceptual assessment*

To evaluate if the proposal is conceptually feasible, the case of MIAPe, a multidimensional healthcare assessment platform, is taken. At the time of writing, 50 different healthcare institutions maintain 5689 assessments from 1156 patients in a centralized manner in MIAPe. In this evaluation, the data is decentralized, assigning the data from their evaluations to each institution. In this way, we try to integrate them following two different approaches: using FedBlocks and using a storage system per institution where each one of them will keep a copy of their data and that of the rest of the institutions (to keep a global view of each patient).

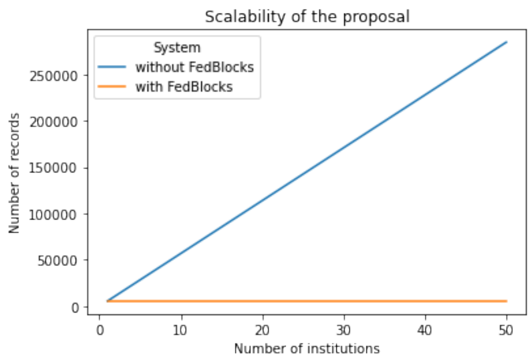


Fig. 2. Number of records as a function of number of institutions sharing their data with or without FedBlocks

Figure 2 shows how FedBlocks keeps the number of records in the system stable, without creating duplicates of each assessment, regardless of the number of institutions sharing their data. However, without FedBlocks, it can be seen how the number of records increases by 5689 each time the data is shared with a new institution. In this way, FedBlocks achieve the main goal of having a complete EHR of each patient, with no duplication between different health systems and no inconsistencies.

[7]https://bitbucket.org/spilab/doctor_app

B. *Performance assessment*

One of the major impediments that are often attributed to the inclusion of blockchain technologies in this type of system is that they are very computationally expensive technologies. As has been done in previous works in the blockchain area [18], the time taken by the system to perform each of the tasks has been evaluated, to consider whether this time is acceptable in comparison with the benefits generated by the proposal.

Some performance measures have been taken using the FedBlocks connector. These metrics are associated with the time it takes to operate the blockchains through the connector when performing read and write operations. The average value (in seconds), as well as the distribution of values around it in 100 different operations of each type, is detailed in Figure 3.

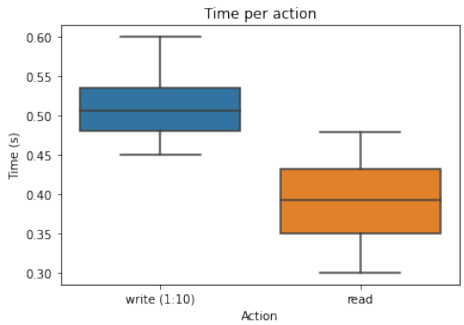


Fig. 3. Times per main actions

As can be seen in this figure, the reading operation is of the order of a few tenths of a second, so it can be considered that it does not impede the user experience. However, the write operation, shown in the graph on a scale of 1:10 for improving readability, is more costly. In this case, adding a record for a patient takes about 5 seconds. This increase in time is caused by the need of generating a block in that patient's actor blockchain and should be balanced against the reduced duplication and inconsistencies provided by FedBlocks.

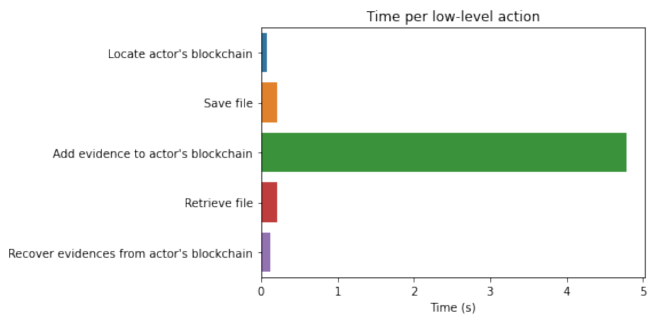


Fig. 4. Times per low-level actions

To verify the above, Figure 4 shows a bar chart reporting in more detail the low-level operations that make up each of the above operations and the average time for each of them. In it, it can be shown that adding evidence —consequently adding a block— to the actor's blockchain of a patient is the most costly operation.

It has also been verified, by modifying the number of institutions subscribed to the system, that the times shown are independent of the number of institutions. This is due to the main blockchain, once a patient is added to the system, is only used to search where their individual blockchain is located.

In contrast, the number of nodes in the patient blockchain can influence the execution times for adding new information, due to the need for consensus between nodes. The data collected in Figures 3 and 4 shows the execution time when there is only one node of the actor blockchain per patient. The times for recovering and adding files through the Resources API depend only on the size of the file and the bandwidth of the internet connection, so no more appreciations have been done on them.

V. Future works and conclusions

The solution proposed in this paper provides an actor-centered storage system to store information in a distributed way and access it jointly. In this way, actors are able to have all their information interoperable, even though it is actually distributed among the different institutions that generate it, reducing the possibility of duplicated information and, consequently, the existence of inconsistencies.

To facilitate the work of software developers who want to use the implemented FedBlocks tool, a connector, and a REST API is offered, which allows connecting with the rest of FedBlocks internal components. These components are deployed in the information systems of the different institutions that integrate their actor' data.

Finally, the proposal of this paper can be controversial because of the need for institutions and services to share their actors' data. Being the essence of the proposal—allowing actor data integration—, it can be misinterpreted as a privacy issue. However, the focus should not be lost on the fact that the proposal seeks a benefit for the actor itself and so it is assumed that, when data protection regulations are complied with and the actors' permission is obtained, the actor will be receptive to the sharing of their data among the different institutions and services that generate it.

As future steps in this proposal, a more complete validation is needed, measuring more metrics and performing scalability tests including throughput and latency metrics—with more blocks, both as more actors and more data per actor, and with more nodes, both as more institutions and more patient's blockchain nodes in different devices—, stress tests and formal comparison with other existent solutions. In this validation, a good idea is examining the time necessary to add evidence to the actor's blockchain, seeing how the number of actor's blockchain nodes affect this time, and searching for any type of optimization in this sense.

Acknowledgment

This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), the FPU19/03965 grant, the Department of Economy, Science and Digital Agenda of the Government of Extremadura (GR18112, IB18030), and the European Regional Development Fund.

References

[1] N. Bui and M. Zorzi, "Health care applications: a solution based on the internet of things," in *Proceedings of the 4th international symposium on applied sciences in biomedical and communication technologies*, 2011, pp. 1–5.

[2] S. J. Henly, J. F. Wyman, and J. E. Gaugler, "Health trajectory research: A call to action for nursing science," *Nursing Research*, vol. 60, no. 3 SUPPL., may 2011.

[3] J. Rojo, J. Hernandez, and J. M. Murillo, "A personal health trajectory api: Addressing problems in health institution-oriented systems," in *Web Engineering*. Cham: Springer International Publishing, 2020, pp. 519–524.

[4] K. Wüst and A. Gervais, "Do you need a blockchain?" in *2018 Crypto Valley Conference on Blockchain Technology (CVCBT)*, 2018, pp. 45–54.

[5] V. Dhillon, D. Metcalf, and M. Hooper, *The Hyperledger Project*. Berkeley, CA: Apress, 2017, pp. 139–149.

[6] P. Bellavista, C. Esposito, L. Foschini, C. Giannelli, N. Mazzocca, and R. Montanari, "Interoperable blockchains for highly-integrated supply chains in collaborative manufacturing," *Sensors*, vol. 21, no. 15, p. 4955, 2021.

[7] B. C. Ghosh, T. Bhartia, S. K. Addya, and S. Chakraborty, "Leveraging public-private blockchain interoperability for closed consortium interfacing," *arXiv preprint arXiv:2104.09801*, 2021.

[8] A. Lohachab, S. Garg, B. Kang, M. B. Amin, J. Lee, S. Chen, and X. Xu, "Towards Interconnected Blockchains: A Comprehensive Review of the Role of Interoperability among Disparate Blockchains," *ACM Computing Surveys*, vol. 54, no. 7, sep 2022.

[9] Z. Wan, M. Cai, X. Hua, J. Yang, and X. Lin, "Blockchain federation enabled trustable internet of things," in *Services – SERVICES 2020*, J. E. Ferreira, B. Palanisamy, K. Ye, S. Kantamneni, and L.-J. Zhang, Eds. Cham: Springer International Publishing, 2020, pp. 61–76.

[10] A. Singh, K. Click, R. M. Parizi, Q. Zhang, A. Dehghantanha, and K.-K. R. Choo, "Sidechain technologies in blockchain networks: An examination and state-of-the-art review," *Journal of Network and Computer Applications*, vol. 149, p. 102471, 2020.

[11] L. Kan, Y. Wei, A. Hafiz Muhammad, W. Siyuan, L. C. Gao, and H. Kai, "A multiple blockchains architecture on inter-blockchain communication," in *2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C)*, 2018, pp. 139–145.

[12] M. Herlihy, B. Liskov, and L. Shrira, "Cross-chain Deals and Adversarial Commerce," *Cross-chain Deals and Adversarial Commerce. PVLDB*, vol. 13, no. 2, pp. 100–113, 2019.

[13] J. Rojo, D. Flores-Martin, J. Garcia-Alonso, J. M. Murillo, and J. Berrocal, "Automating the interactions among iot devices using neural networks," in *2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE, 2020, pp. 1–6.

[14] A. Dubovitskaya, P. Novotny, S. Thiebes, A. Sunyaev, M. Schumacher, Z. Xu, and F. Wang, "Intelligent health care data management using blockchain: current limitation and future research agenda," in *Heterogeneous Data Management, Polystores, and Analytics for Healthcare*, 2019, pp. 277–288.

[15] N. Deepa, Q.-V. Pham, D. C. Nguyen, S. Bhattacharya, B. Prabadevi, T. R. Gadekallu, P. K. R. Maddikunta, F. Fang, and P. N. Pathirana, "A survey on blockchain for big data: Approaches, opportunities, and future directions," 2021.

[16] Y. Guo and C. Liang, "Blockchain application and outlook in the banking industry," *Financial innovation*, vol. 2, no. 1, pp. 1–12, 2016.

[17] J. Rojo, J. Hernandez, S. Helal, J. M. Murillo, and J. Garcia-Alonso, "Blockchain-supported health registry: the claim for a personal health trajectory traceability and how it can be achieved," in *International Workshop on Gerontechnology*. Springer, 2022.

[18] L. Foschini, A. Gavagna, G. Martuscelli, and R. Montanari, "Hyperledger fabric blockchain: Chaincode performance analysis," in *ICC 2020-2020 IEEE International Conference on Communications (ICC)*. IEEE, 2020, pp. 1–6.

Chapter 7

Analyzing the Performance of Feature Selection on Regression Problems: A Case Study on Older Adults' Functional Profile

Authors: *Javier Rojo, Lara Guedes de Pinho, César Fonseca, Manuel José Lopes, Sumi Helal, Juan Hernández, Jose Garcia-Alonso, Juan Manuel Murillo.*

Publication type: *Journal article.*

Journal:*IEEE Transactions on Emerging Topics in Computing.*

Year of publication: *2022.*

DOI: *10.1109/TETC.2022.3181679*

2021 JCR IF (Rank): *6.595 (Q1 26/164)*

Analyzing the Performance of Feature Selection on Regression Problems: a Case Study on Older Adults' Functional Profile

Javier Rojo, Lara Guedes de Pinho, César Fonseca, Manuel José Lopes, Sumi Helal, Juan Hernández, Jose Garcia-Alonso, Juan M. Murillo

Abstract—Healthcare systems are capable of collecting a significant number of patient health-related parameters. Analyzing them to find the reasons that cause a given disease is challenging. Feature Selection techniques have been used to address this issue—reducing these parameters to a smaller set with the most "determinant" information. However, existing proposals usually focus on classification problems—aimed to detect whether a person is or is not suffering from an illness or from a finite set of illnesses. However, there are many situations in which health professionals need a numerical assessment to quantify the severity of an illness, thus dealing with a regression problem instead. Proposals using Feature Selection here are very limited. This paper examines several Feature Selection techniques to gauge their applicability to the regression-type problems, comparing these techniques by applying them to a real-life scenario on the functional profiles of older adults. Data from 829 functional profiles assessments in 49 residential homes were used in this study. The number of features was reduced from 31 to 25—with a correlation between inputs and outputs of 0.99 according to the R^2 score and a Mean Square Error (MSE) of 0.11—or to 14 features—with a correlation of 0.98 and MSE of 5.73.

Index Terms—Feature Selection, Regression, Machine Learning, Aging Informatics, Healthcare Data Analytics, eHealth

1 Introduction

Every day, healthcare professionals need to assess large numbers of patients—not only those with chronic or degenerative diseases but also those with long-term or chronic conditions [1]. This requires a constant reassessment of patients, especially for the aging population, among whom chronic and degenerative diseases and dysfunctions are more common and more frequent. Many of these assessments involve collecting large amounts of information regarding different variables associated with the patients' health status [2]. To help health professionals manage data from these assessments, many healthcare systems have IT platforms where their patients' information is digitized [3] into Electronic Health Records, allowing health professionals, with the help of software developers and data scientists, to develop powerful assessment platforms [4].

Nevertheless, the effort needed for health professionals and informal caregivers to perform these assessments remains excessive. Collecting data from several variables in each assessment is time-consuming which infringes on their limited time and reduces their patient-facing care time [5]. Health professionals are thus forced to reduce the number of assessments that they need to perform routinely to care for their patients, thus reducing the sustainability and quality of care.

If a clinical assessment includes redundant or irrelevant variables, then the initial set of inputs could potentially be reduced at a minimal accuracy loss, consequently easing the aforementioned time crunch situation. An example of this is the World Health Organization Disability Assessment Schedule II (WHODAS-II), an assessment instrument for functioning. Although the original version included 36 items, some studies have validated the use of a reduced 12-item version [6], [7]. However, establishing which variables contain redundant information and can therefore be eliminated is not a trivial matter. The selection cannot be done manually, based on intuition or using arbitrary techniques to find relationships between variables. Instead, statistical techniques are needed to calculate which reduced set of variables provides the same information as the original set [8]. After this, calculations done to extract results with these items must be reformulated or replaced by other techniques—since the new set does not contain all items of the original one.

To solve this problem, two types of techniques exist in the literature, which can be used together. First, Feature Selection techniques [8] allow selecting from among a set of features those that best describe the output, eliminating redundant, unrelated, or non-influential variables. Second, Machine Learning and Deep Learning techniques can be used to define models that automatically learn from data to establish relationships between input variables and an output that has not been programmed or defined beforehand—a prediction model. These techniques are already employed in the health domain to solve problems involving the analysis of different kinds of data [9], [10], [11].

- *J. Rojo, J. Hernández, J. Garcia-Alonso, and J. M. Murillo are with the Department of Computer and Telematics Systems, University of Extremadura, Spain. E-mail: {javirojo, juanher, jgaralo, juanmamu}@unex.es*
- *S. Helal is with the University of Florida, USA. Email: helal@cise.ufl.edu*
- *L. Guedes de Pinho, C. Fonseca, and M. J. Lopes are with the University of Évora and the Comprehensive Health Research Centre (CHRC), Portugal. Email: {lmgp, cfonseca, mjl}@uevora.pt*

Manuscript received December XX, 2021; revised December XX, 202X.

Feature Selection and Machine Learning/Deep Learning techniques are closely related. Feature Selection techniques are employed to pre-process the input variables in any of the main types of Machine Learning and Deep Learning problems [10]: classification —the output is one or several among a series of well-known classes—, regression —the output is a continuous value—, and clustering —the output is a series of clusters not known previously, to which the different samples belong. This pre-processing is often conducted as part of the data cleansing phase [9], [12]. Feature Selection is frequently used in classification problems [8], [13], [14]. The use of Feature Selection in unsupervised problems, such as clustering, has also been extensively researched for years [15]. However, as far as the authors are aware, Feature Selection is not commonly applied to regression problems [16], [17] and its potential could be investigated further [18].

This paper aims to offer a technological solution that can be used to reduce the number of items to be measured in a health assessment, allowing the diagnosis of a pathology or condition to be accomplished with almost the same precision but with less data. To do this, different feature selection techniques used in regression problems and available in the literature have been reviewed. In order to compare them, these techniques are applied to a real-world case study focused on the assessment of aging adults' functional profiles. This comparison allows us to propose new models to predict functional profiles' scores with fewer variables than the original formulas. The results obtained by the model in terms of correlation between inputs and outputs are also analyzed. They provide an overview of the performance of feature selection techniques when applied to regression problems in the case study. They also provide insights into their extrapolation to other problems of this type—in other healthcare assessments as well as other application domains.

The paper is organized as follows. First, Section 2 introduces Dimensionality Reduction and its Feature Selection techniques. Section 3 provides an overview of the structure and process followed in the development of the proposal and introduces the case study. Section 4 compares each of the alternative feature selection techniques, by using them—independently or in combination—to predict target variables based on the older adults' functional profile dataset. Section 5 discusses the results in terms of number of features and achieved correlation between inputs and outputs, and compares the initial set of variables with the final set. Section 6 is a brief discussion about Feature Selection on regression problems and the results obtained in the case study focused on in this paper. Section 7 reviews existing literature on the use of Feature Selection on healthcare data. Finally, Section 8 presents the paper's conclusions and an agenda for future work in this research area.

2 Background

The increasingly high dimensionality and complexity of data make it necessary to use Dimensionality Reduction (DR) techniques [19] in exploratory data analysis. Feature Selection is a type of DR technique that allows data scientists to move from an initial high dimensional data set to a more reduced one, known as the intrinsic dimension of data. This intrinsic dimension contains the minimum features that describe the data [20], providing a series of benefits: simplification of prediction models based on these data, improvement of its predictions, or avoidance of the long-standing problem known as the "curse of dimensionality" [21], among others. These benefits are common to all types of DR techniques. However, each one has its own intrinsic advantages, depending on how dimension is reduced in each of them.

Feature Selection methods [22] reduce the data dimensionality by selecting a subset of variables from the input. This subset describes the input data while reducing the adverse effects due to including noise and irrelevant variables in predictions [8]. Therefore, they aim to simplify prediction models, improving their results—namely better generalization and reduced overfitting—and problem understanding. They also reduce the amount of information to be collected as input, and thus the computational load and fit time, while avoiding the above-mentioned curse of dimensionality. For these reasons, Feature Selection methods are particularly useful in domains with many input features and few samples [23]—i.e., analysis of DNA micro-arrays data or handwritten manuscripts—especially in classification problems.

These techniques are based on the premise that, in many models, the input information that allows characterizing an output—for example, discriminating between different classes in a classification problem—can be obtained from a smaller set of variables than initially used. This could be due to mutually-dependent variables—where the value of one is highly correlated with the value of another—or due to irrelevant input variables, whose values do not affect the output—even though they were initially believed that they would. The former introduces redundant information (and complexity) in the models, while the latter could lead to noise and bias in the prediction. Feature Selection eliminates redundant and irrelevant features at a minor loss of information, and hence model accuracy, in both supervised and unsupervised problems.

Feature Selection is different from other DR methods [24] such as Feature Extraction. Feature Extraction methods generate a set of new features based on the initial ones with each new feature containing the most relevant information from several of the initial ones. Such Feature Extraction set might or might not be smaller than the initial set. Feature Selection, on the other hand, filters the most relevant, existing features without generating new ones, only eliminating some. For this reason, Feature Selection is better suited to the healthcare sustainability problem addressed in this work. However, when predictions need to be improved, both methods can be applied together—first Feature Selection and then Feature Extraction on the resulting features.

There are three main types of Feature Selection methods in the existing literature [8], [22]: filter, wrapper, and embedded methods. Filter methods are independent of the prediction model that is subsequently used, where the selection of the most relevant variables is based on a ranking criterion. The ranking is arrived at using a well-defined criterion used to establish the relationships between each input variable and the output variables. Wrapper methods [25] work differently by employing and evaluating a prediction model to each subset of the variables. Performance for each subset is measured as a function of the prediction accuracy provided by the model trained with that subset. This model is then "wrapped" in a search algorithm for the best-performing subset. Finally, embedded methods also employ a prediction model to determine the best subset of input variables. However, in this case, feature selection is performed as part of the model's training process, rather than based on the predictions yielded by an already trained model. Therefore, there is no need to split the data into a training and a testing set—to train first and then evaluate the prediction model's performance later—thus reducing the Wrapper methods' computational cost.

These methods are not mutually exclusive and can be used together [26]. For instance, the filter methods, being less computationally expensive and more independent regarding the prediction model to be subsequently used but also less aggressive in terms of feature sifting, are usually applied first to perform an initial phase of feature selection, which amounts to pre-processing the set of variables that will subsequently be analyzed using one of the other two techniques.

In addition to Feature Selection techniques, this paper also employs Machine Learning models. These techniques can be divided into supervised, unsupervised, and reinforced learning, depending on the type of problem to be addressed. Learning is considered supervised when there is a set of labeled data —both the input and the output are known. Supervised learning includes problems of classification or regression, depending on what is to be learned. This paper will focus on supervised learning and, more specifically, on regression problems.

3 Proposed approach

The proposal in this paper is the result of an experimental study carried out in several phases. All the experiments were conducted using real-life data from a single case study: an evaluation of the aging adults' functional profile. The specific data used were derived from 829 assessments of 716 older adults treated in 49 residential homes and medical centers in Portugal. These assessments are employed to compute five different continuous values that describe the aging adults' functional profile, making this case study a regression study.

The first phase involved examining available examples of using Feature Selection techniques in regression problems. Quantitative comparison was carried out considering different aspects to evaluate the performance of each technique when applied to our case study.

Then, the best performing techniques were selected to create a series of models that, using a reduced set of input features, could predict the functional profile of the older adults studied with almost the same precision as the original set. In order to measure this accuracy, we provide a series of metrics on the correlation between inputs and outputs and the error introduced in the prediction models, compared to the traditional method using all the input features.

3.1 Case Study: Evaluation of Functional Profile using the Elderly Nursing Core Set (ENCS)

The experiment performed is associated with the authors' Multidimensional Integrated Assessment Platform for elderly (MIAPe) [4], which is employed by health professionals and caregivers in different Portuguese socio-geriatric settings. It is used to assess different aspects of the patients' health including the patients' functional profile which is the most relevant to the work in this paper. For this purpose, 31 items or questions—the input variables—are collected, with values filled manually using the Elderly Nursing Core Set (ENCS) form [27].

The ENCS was developed by Lopes and Fonseca in 2013 to assess the quality of life in terms of functioning among older adults [28]. The psychometric properties of the ENCS were later evaluated by Fonseca et al. [27]. This assessment instrument is based on the International Classification of Functioning, Disability and Health (ICF) [29]. Each of the 31 questions is valuated on a Likert scale from 1 to 5 points: (1) No disability: 0–4%; (2) Mild disability: 5– 24%; (3) Moderate disability: 25–49%; (4) Severe disability: 50–95%; and (5) Complete disability: 96–100%. From these 31 items, 10 items measure body functions, 17 items measure body structure, and 4 items measure environmental factors. Full description of these items can be found in the supplementary material. The ENCS is divided into four areas of concern: self-care, learning and mental functions, communication, and social relationships. A higher value is correlated with a worse functional profile of the assessed individual. Applying a series of validated mathematical formulas [27] to the values of these 31 questions, five scores corresponding to the above-mentioned areas of concern are extracted. These represent the general functional profile of the elderly: *General punctuation of functionality* (GPF), *Self-care* (AC), *Learning and memory functions* (LMF), *Communication* (C), and *Relationships with friends and carers* (RFC). These scores are represented as continuous values, from 0 to 100.

- **General punctuation of functionality** corresponds to the overall score obtained in the functional profile for all dimensions. For its calculation, all items are employed.
- **Self-care** corresponds to the basic activities of daily living, such as eating and drinking. For its calculation, all 17 items from body structure are employed.
- **Learning and memory functions** is concerned with cognitive functions, such as memory or orientation. For its calculation, all 10 items from body functions are employed.
- **Communication** is related to the ability to talk or hold a conversation. For its calculation, 4 of the 17 items from body structure are employed.
- **Relationships with friends and carers** corresponds to the ability to maintain relationships with family or obtain support from health professionals, friends, or other caregivers. For its calculation, all 4 items from environmental factors are employed.

Each of these scores can be represented as a regression function that takes as input each of the 31 questions of the ENCS form, making this case study a suitable one for the intended scope. Therefore, in this case study the focus will be put on being able to compute each of these five scores with a reduced number of questions—instead of the 31 original ones.

4 Comparison of Feature Selection Techniques on Functional Profile

To determine the best Feature Selection technique to be applied to the case study, the different techniques available for Feature Selection on regression problems were compared. As far as the authors know, no previous study has compared the application of different Feature Selection techniques on regression problems.

To carry out this comparison, a battery of different Feature Selection techniques has been chosen, following a well-structured process— to make the comparison as fair and reproducible as possible. All the results obtained were meticulously documented to ensure replicability. The techniques selected, the methodology followed, and the results obtained are discussed next.

4.1 Selected Feature Selection Techniques

The Feature Selection techniques used in this study are commonly available in Data Science tools. Specifically, we used the Python programming language, which is widely used in the field of Data Science and Data Mining. Therefore, only techniques offered for this language were sought. Techniques were selected from Scikit-learn[1] and Yellowbrick[2] Data Science libraries. The first is a widely used library for the creation of Machine Learning models that also offers DR tools. The second is a Scikit-learn wrapper that offers visual solutions to facilitate model and data analysis.

Limiting the study to only techniques available in Python and, more specifically, offered by these libraries, may suggest that certain techniques were left out of the comparison—for instance, those that are less common. However, given the large number of techniques offered by these libraries—as shown below—, we consider that the obtained results in the comparison are sufficiently valid—since we have included very common and frequently used Feature Selection techniques such as Recursive Feature Elimination (RFE) and filter methods based on the correlation between features and Mutual Information (MI). Moreover, from a practical viewpoint, using techniques offered by libraries that are widely used in production environments facilitates the availability, reproducibility, and transfer of results of this research.

All Feature Selection techniques available in both libraries were evaluated. For each technique, different parameter combinations were tested. Compared Feature Selection techniques are shown in Table 1.

Type	Technique	Library
Filter	GenericUnivariateSelect	Sklearn
Filter	SelectPercentile	Sklearn
Filter	SelectKBest	Sklearn
Filter	SelectFpr	Sklearn
Filter	SelectFdr	Sklearn
Filter	SelectFwe	Sklearn
Filter	VarianceThreshold	Sklearn
Filter	Rank1D	Yellowbrick
Filter	Rank2D	Yellowbrick
Filter	Feature Correlation	
Embedded	SelectFromModel	Sklearn
Embedded	SequentialFeatureSelector	Sklearn
Embedded	RFE	Sklearn
Embedded	RFECV	Sklearn
Embedded	Feature Importances	Yellowbrick
Embedded	RFECV	Yellowbrick

TABLE 1
List of techniques evaluated

No wrapper method was tested since these libraries offer embedded methods instead.

4.2 Methodology

Our comparison evaluated the different techniques based on the number of features selected, the correlation achieved by Machine Learning models using those features, and the execution time required to select the features. Correlation is measured with the coefficient of determination, R^2 score, with 1.0 being the ideal value—indicating that model that perfectly explains the observed output variation concerning input variation—and 0 being the worst-case scenario—model that does not explain any variation—. Negative values are not taken into account. In contrast to other metrics, the closer the R^2 score is to 1, the better the model explains the variability of the target feature (output). Other metrics, such as Mean Square Error (MSE), must be considered when training a final model. However, to assess how changes in input features affect the model's output, only the R^2 score was considered in this comparison.

To execute the different techniques we used a laptop running Windows 10, with 16 GB of RAM and an Intel Core i7-8550U processor at 1.8 GHz base frequency and 4.0 GHz turbo frequency, equipped with NVMe SSD technology for storage. The following software was used: Python v.3.7.5 (programming language), Anaconda v.1.9.12 (Python distribution for Data Science), conda v.4.10.1 (package management system), Jupyter v.6.0.1 (development environment), Scikit-Learn v.0.23.0 (Data Science library), Yellowbrick v.1.2 (Data Science library), and Pandas v.0.25.3 (data manipulation and analysis library).

The process followed to carry out the comparison was as follows:

Step 1: Transform functional profile data into a suitable format. The Elderly Nursing Core Set (ENCS) data was anonymized and filtered to obtain a dataset containing only information on the form's 31 items and the values for each of the five scores of the functional profile of the older adults (GPF, AC, LMF, C, and RFC).

Step 2: Test the initial feature set data, without applying Feature Selection techniques, on 12 different Scikit-learn regression models. These 12 models were generated with the main Scikit-learn algorithms for regression models —based on the assumption that linear regression, logistic regression, support vector machines, and tree-based algorithms are the most employed for regression problems [30]. All parameters were left as default. Since there are five outputs, five models had to be created with the same inputs—one for each output. In this case, we took advantage of Scikit-learn's MultiOutputRegressor class, which internally creates one

1. https://scikit-learn.org/stable/
2. https://www.scikit-yb.org/en/latest/

model for each output and then encapsulates them in one. The results were obtained with an initial set of 829 samples, corresponding to evaluations of actual patients, dividing them into 555 for training and 274 for testing. This is a typical division of roughly two parts for training and one for testing. Then a hold-out validation was performed—training and testing sets without cross-validation.

Step 3: Select the five models with the best predictions (best R^2) out of the 12 models tested in the previous step. This is possible because the initial feature set is easily computable and allows the testing of different algorithms.

Step 4: Test the Feature Selection algorithms. For each of these methods, different configurations were tested, based on the different hyperparameters that they accept:

- In those that required keeping a number of features, such as K, percentile or the maximum number of features to be selected, the value was initially set to half —15 features or a percentile of 50%. This decision has been taken because the objective in the step is to make an initial comparison between the different techniques and not to find the optimal value of hyperparameters for each of them—or even compare the results for the same one with different hyperparameter values. This is done later in Step 6.
- In those using a threshold, different values were tested.
- Values such as *alpha*, employed by techniques such as SelectFpr or SelectFdr, were left as default.
- For the embedded methods, each of the five models selected in Step 3 was tested as estimators. This estimator model is the one being wrapped by the embedded method to determine the importance of each feature and can be different from the final prediction model where the set of features selected is employed as input.
- Methods using a model as estimator required one estimator for each output and thus were not compatible with MultiOutputRegressor. This required performing a feature selection for each of the five outputs, before merging the results. This merge is done by joining the selected features for each output so that the resulting set of features allows predicting the five functional profile scores —the five outputs.

Step 5: Evaluate the performance of the selected feature set for each technique and hyperparameter configuration, again using the prediction models selected in Step 3. The results are provided in terms of the final number of features, R^2 score for each of the five models evaluated, average R^2 score, and execution time of the Feature Selection process. To calculate the R^2 score for each model, we used the same division of samples and validation as in Step 3.

Step 6: Those methods that could be configured using parameters were executed again, using the whole range of possible values. Results were complemented with a graph per each technique and configuration, showing the evolution of the number of resulting features for each different value of the parameters and the average R^2 score associated with each number of variables. This score was calculated using the same functions as in Step 5.

All the software developed for the benchmark is provided as additional material and in a Zenodo repository[3]. The complete comparison can be replicated by running the "Comparison" and "Graphical" notebooks.

4.3 Comparison of Results

The main outcomes of the different steps of the comparison are shown below. A more complete version of the tables presented here, and additional figures with the results of varying the parameters' values when using the different techniques, can be found as additional resources and in the aforementioned Zenodo repository.

From **Step 1**, no outcomes are obtained. This step is only for data processing.

From **Step 2** the Table 2 is obtained. This table shows the results obtained when evaluating the different models, using all 31 features—without Feature Selection. As can be seen, the results in most of the tested models are close to 100% correlation (1.0 R^2 score). Only Support Vector Regressor (SVR) with a non-linear RBF kernel yielded lower correlation results (0.74 R^2 score). On the other hand, the third-degree Polynomial Regression yielded a negative and out-of-bounds result. According to the Scikit-learn library that provides the implementation of the algorithm and the calculation of the coefficient of determination, the negative result is due to the model output being very different from that expected for the same input values [31].

To ensure that the R^2 score obtained by these models is not the result of overfitting and that default hyperparameters are not leading the models to a suboptimal point, a 5-step cross-validation with the training data has been carried out, showing that the results are good and acceptable. The standard deviation between the R^2 score of each step has been analyzed and, except for the SVR with RBF kernel and NuSVR, the values obtained are in the order of 10^{-3} to 10^{-5}. The exact results can be found in the Jupyter notebook *Initial_tests_CV* in the supplementary material.

The five models with a coefficient of determination higher than 0.99—Linear Regression, Ridge Regression, Lasso Regression, Extra Tree Regression, and LinearSVR—were selected in **Step 3**.

As well, Table 2 shows the time needed to train the model and to perform a prediction for each of the tested models. Neural Network Regression is the one offering the worst training time, followed by Random Forest, Extra Tree, and Polynomial Regression of Degree 3. This situation is expected since these are the more complex models. Prediction times are in the order of microseconds in most cases, with the costly ones being the Random Forest and Extra Tree methods again, as well as some implementations of the SVR. These are from the order of tenths of milliseconds. However, times for both cases, train and prediction, are acceptable in any of the models and their consideration is not as important as R^2 for that case—no need for constant retraining or fast prediction exists in our case study.

Step 4 and 5 start at that point, having the results of the five models selected when they are trained with the original features set. In these steps, the aim is to obtain the results for the same models when they are trained with the

3. https://doi.org/10.5281/zenodo.6421873

Model	R^2	Train time (s)	Predict time (s)
Linear Regression	0.999659	0.0102	$7.40x10^{-6}$
Polynomial Regression (Degree=2)	0.885259	0.3103	$3.13x10^{-5}$
Polynomial Regression (Degree=3)	-220.837775	1.0423	$9.73x10^{-5}$
Ridge Regression	0.999657	0.0182	$8.63x10^{-6}$
Lasso Regression	0.990675	0.0124	$1.09x10^{-5}$
Decision Tree Regression	0.957315	0.0201	$1.09x10^{-5}$
Random Forest Regression	0.983631	1.3971	$2.06x10^{-4}$
Extra Tree Regression	0.990431	1.1709	$1.85x10^{-4}$
SVR (kernel=rbf)	0.745581	0.1036	$3.01x10^{-4}$
LinearSVR	0.998442	0.2315	$7.29x10^{-6}$
NuSVR	0.721767	0.0623	$1.53x10^{-4}$
Neural Network Regression	0.978924	2.6033	$3.72x10^{-5}$

TABLE 2
Results of model testing without feature selection

set of features selected by each Feature Selection technique (and each of its parameters' configurations) tested in this study. Tables 3 and 4 show the summary of the results obtained for each of these techniques in different terms: the number of features selected, average train time (in seconds), and R^2 score when the set of features selected is used as the input set to train each of the five models under study. Table 3 shows the results of the filter methods and their configurations while Table 4 shows results for the embedded ones. As can be seen in both tables, the results obtained are related to the number of features considered, execution time (in seconds), and correlation—the R^2 score obtained in Step 5 of comparison with the set of features selected on each of the five models selected of the Table 2 during Step 3 and on average. As was the case in Step 2, a 5-step cross-validation has been carried out here in addition to the traditional validation as well, to check that the models used and their configuration are still valid and do not suffer from overfitting. The results of this cross validation can be found in the Jupyter notebook *Comparison_CV* of the supplementary material. All possible configuration and techniques available in the libraries employed have been tested. However, those configurations or techniques not working have been discarded and are not shown in the tables of results to improve readability. That is the reason why some techniques listed in Table 1 are not shown on them. Their results can be found in the supplementary material attached to this manuscript.

In the tables, tuples containing only results in terms of execution time belong to techniques that provide visual results, that is, that do not automatically filter features. Instead of that, they provide some graphs that experts in the domain must interpret to manually filter the features by themselves. Since such results are subject to expert interpretation, they do not provide direct information in terms of the number of features selected and/or results of the models trained with it. Hence, all these tuples are listed in the tables to indicate that they have been tested. However, none of them will be delved into further in this comparison.

Regarding the results, we will consider first the **time required to perform the feature filtering** —which offers an insight into how computationally costly each of the techniques employed can be. This time is only relevant for the beginning, when the features are selected. After that, it will not be necessary to re-execute these techniques. In this regard, it can be observed that the average time of the filter methods (*Time* column of *Average results* row in Table 3) is much lower than the average time of the embedded methods (*Time* column of *Average results* row in Table 4). However, this is mainly due to the time required for the RFECV technique of the *yellowbrick* library when using Linear SVR as estimator. If the time required by that technique with that configuration is not taken into account, the average time of the embedded methods is significantly reduced to 4.37 seconds. Therefore, it can be concluded that filtering methods are, on average, slightly faster than embedded methods. Specifically, embedded methods' time is 663% that of filter ones if the time of the RFECV with Linear SVR as estimator is discarded. However, and especially taking into account the duration of the execution times obtained by using any of the methods considered—mostly in the order of tenths and hundredths of seconds, the results are manageable and do not affect the decision of which one should be used in this case study.

If we focus only on the times obtained by the embedded methods, the situation arising from using a Linear SVR as estimator in the RFECV technique appears not to be an isolated case —although this is the most outstanding example. In all embedded methods, applying a Linear SVR as estimator notably increases the execution time by 1953% —from 4.61 seconds on average for other techniques and configurations to 90.06 seconds on average for those using a Linear SVR as estimator. Conversely, the model that offers the best estimator times in the embedded methods is the Ridge Regression, although with results very similar to those offered by the other three models.

It is noticeable, however, that the embedded techniques from the Yellowbrick library —Feature Importances technique and RFECV (yellowbrick version)— have much longer execution times than the techniques taken from Scikit-learn. This is probably because this library works as a wrapper over Scikit-learn—taking the same amount of time as if they were executed directly—and then generating graphical solutions based on the results obtained. The time requirements of these techniques are even more remarkable in the case of RFECV, whose fastest configuration — using a Linear Regression as estimator— needs 74 times the time of the slowest Scikit-learn technique with the same configuration—RFE with a Linear Regression as estimator.

On the other hand, if we focus only on the times obtained by the filter methods, we can appreciate that the use of the *mutual_info_regression* as score function leads to a notable increase in the times. Specifically, the use of this score function instead of *f_regression* leads to an increase in time of 11458% in the techniques that allow both score functions— 0.02 seconds on average with *f_regression* and 2.34 seconds on average with *mutual_info_regression*. In addition, as with the embedded methods, the Yellowbrick techniques also require longer times than the others. These are the only methods whose results reach times in the order of seconds or tenths of seconds—without taking into account techniques employing *mutual_info_regression* as score function.

Next, we will discuss the **number of features selected** by each technique. It is important to mention at this point that in most cases the number of features selected by each technique does not match the number of maximum, k best—*k* being the number of best features to be selected— and percentile features indicated for the technique. This is due to the existence of five outputs in our case study.

					R^2 score					
Feature Selection technique	Score func. / Algorithm	Parameters	N. features	Time (s)	LR	Ridge	Lasso	Extra Tree	LinearSVR	Avg.
GenericUnivariateSelect	f_regression	percentile(50)	**26**	**0.030751**	0.999662	0.999661	0.991935	0.959194	0.999570	**0.990004**
GenericUnivariateSelect	mutual_info_regression	percentile(50)	**26**	**2.134323**	0.999662	0.999661	0.991935	0.962304	0.999617	**0.990636**
GenericUnivariateSelect	f_regression	k_best(15)	**26**	**0.018815**	0.999662	0.999661	0.991935	0.957074	0.999595	**0.989585**
GenericUnivariateSelect	mutual_info_regression	k_best(15)	**26**	**1.907155**	0.999662	0.999661	0.991935	0.956841	0.999618	**0.989543**
GenericUnivariateSelect	f_regression	fpr	**29**	**0.020798**	0.999660	0.999659	0.990675	0.959773	0.996560	**0.989265**
GenericUnivariateSelect	f_regression	fdr	**29**	**0.017323**	0.999660	0.999659	0.990675	0.957852	0.997536	**0.989076**
GenericUnivariateSelect	f_regression	fwe	**29**	**0.028273**	0.999660	0.999659	0.990675	0.957720	0.998158	**0.989174**
SelectPercentile	f_regression	percentile(50)	**26**	**0.016828**	0.999662	0.999661	0.991935	0.960177	0.999587	**0.990204**
SelectPercentile	mutual_info_regression	percentile(50)	**26**	**2.680883**	0.999662	0.999661	0.991935	0.960406	0.999616	**0.990256**
SelectKBest	f_regression	k(15)	**26**	**0.021328**	0.999662	0.999661	0.991935	0.962586	0.999604	**0.990690**
SelectKBest	mutual_info_regression	k(15)	**26**	**1.932915**	0.999662	0.999661	0.991935	0.964257	0.999524	**0.991008**
SelectFpr	f_regression	alpha(0.05)	**30**	**0.017359**	0.999659	0.999657	0.990675	0.956662	0.999236	**0.989178**
SelectFdr	f_regression	alpha(0.05)	**30**	**0.016368**	0.999659	0.999657	0.990675	0.963822	0.998723	**0.990507**
SelectFwe	f_regression	alpha(0.05)	**30**	**0.016368**	0.999659	0.999657	0.990675	0.956609	0.998340	**0.988988**
VarianceThreshold		threshold(0)	**31**	**0.011376**	0.999659	0.999657	0.990675	0.951833	0.999485	**0.988262**
VarianceThreshold		threshold(0.5)	**30**	**0.012895**	0.990122	0.990139	0.983033	0.948834	0.987646	**0.979955**
VarianceThreshold		threshold(0.8)	**26**	**0.014385**	0.950137	0.950143	0.940121	0.835992	0.933441	**0.921967**
Rank1D	algorithm="shapiro"			**0.266352**						
Rank2D	algorithm="pearson"			**0.514352**						
Rank2D	algorithm="covariance"			**0.467696**						
Rank2D	algorithm="spearman"			**0.499440**						
Rank2D	algorithm="kendalltau"			**0.775745**						
Feature Correlation	method="pearson"			**1.325842**						
Feature Correlation	method="mutual_info-regression"			**3.091538**						
Average results of Scikit Learn			28	0.52342	**0.996186**	**0.996187**	**0.987845**	**0.951290**	**0.994462**	**0.985194**
Average results of Yellowbrick				0.99157						
Average results			28	0.659963	**0.996186**	**0.996187**	**0.987845**	**0.951290**	**0.994462**	**0.985194**

TABLE 3
Results with filter feature selection methods

					R^2 score					
Feature Selection technique	Estimator	Parameters	N. features	Time (s)	LR	Ridge	Lasso	Extra Tree	LinearSVR	Avg.
SelectFromModel	Linear Regression		**25**	**0.019840**	0.999661	0.999660	0.991935	0.956487	0.999528	**0.989454**
SelectFromModel	Ridge Regression		**25**	**0.017359**	0.999661	0.999660	0.991935	0.969842	0.999629	**0.992145**
SelectFromModel	Lasso Regression		**26**	**0.018350**	0.999662	0.999661	0.990675	0.963172	0.998009	**0.990236**
SelectFromModel	Extra Tree Regression		**15**	**0.029721**	0.989018	0.989018	0.981734	0.949199	0.987603	**0.979314**
SelectFromModel	Linear SVR		**25**	**0.472687**	0.999661	0.999660	0.991935	0.965365	0.999622	**0.991249**
RFE	Linear Regression	step=1. n_features_to_select(0.5)	**19**	**0.184014**	0.995868	0.995877	0.988012	0.956765	0.995921	**0.986488**
RFE	Ridge Regression	step=1. n_features_to_select(0.5)	**19**	**0.168639**	0.995872	0.995876	0.988544	0.962146	0.995824	**0.987653**
RFE	Lasso Regression	step=1. n_features_to_select(0.5)	**19**	**0.252960**	0.993647	0.993647	0.985406	0.957668	0.992244	**0.984522**
RFE	Extra Tree Regression	step=1. n_features_to_select(0.5)	**18**	**0.342241**	0.994401	0.994401	0.986994	0.961540	0.994313	**0.986330**
RFE	Linear SVR	step=1. n_features_to_select(0.5)	**18**	**6.788760**	0.994438	0.994437	0.987052	0.958555	0.994463	**0.985789**
Feature Importances	Linear Regression	topn=15. stack=false,relative=true		**1.870455**						
Feature Importances	Ridge Regression	topn=15. stack=false,relative=true		**1.721119**						
Feature Importances	Lasso Regression	topn=15. stack=false,relative=true		**1.874882**						
Feature Importances	Extra Tree Regression	topn=15. stack=false,relative=true		**1.906664**						
Feature Importances	Linear SVR	topn=15. stack=false,relative=true		**2.007809**						
RFECV (yellowbrick)	Linear Regression	step=1. cv=5	**25**	**13.765470**	0.999661	0.999660	0.991935	0.959631	0.999592	**0.990096**
RFECV (yellowbrick)	Ridge Regression	step=1. cv=5	**25**	**14.980706**	0.999661	0.999660	0.991935	0.959212	0.999561	**0.990006**
RFECV (yellowbrick)	Lasso Regression	step=1. cv=5	**25**	**17.979028**	0.999661	0.999660	0.991935	0.959729	0.999610	**0.990119**
RFECV (yellowbrick)	Extra Tree Regression	step=1. cv=5	**27**	**18.757748**	0.999552	0.999550	0.991866	0.961919	0.999535	**0.990484**
RFECV (yellowbrick)	Linear SVR	step=1. cv=5	**29**	**351.008670**	0.999662	0.999660	0.991935	0.951663	0.999586	**0.988501**
Average results of Scikit Learn			**21**	**0.82946**	**0.99619**	**0.99619**	**0.98842**	**0.96007**	**0.99572**	**0.98732**
Average results of Yellowbrick			**26**	**42.58725**	**0.99964**	**0.99964**	**0.99192**	**0.95843**	**0.99958**	**0.98984**
Average results			**23**	**21.708356**	**0.997339**	**0.997339**	**0.989589**	**0.959526**	**0.997003**	**0.988159**

TABLE 4
Results with embedded feature selection methods

Therefore, to select the appropriate features for each output, all techniques must be applied five times on the original set of features. After this, the selected features per output are merged to obtain the total required set of features. This way, selecting the 15 best features (k=15) for each output may result in a final set of 26 features —a result yielded by some of the techniques. It should also be pointed out that, in this case, the embedded techniques yield more remarkable results than the filter techniques. The former selected 23 features on average (*N. features* column of *Average results* row in Table 4), while the latter selected an average of 28 features (*N. features* column of *Average results* row in Table 3).

In the case of embedded methods, the RFE technique yielded sets with fewer than 20 features for any of the estimators tested. Specifically, Extra Tree Regression and Linear SVR are the ones that filtered most features, reducing the set to 18 features compared to the 19 features obtained with the other estimators. The same happens with the SelectFromModel when using the Extra Tree Regression as estimator again. When using this estimator the number of features is reduced to 15, compared to the 25-26 selected when using other estimators, without a remarkable loss of correlation.

Regarding filter methods, the number of features can at best be reduced by five, resulting in sets of 26 features. Several techniques and configurations result in this number of features being selected. However, there are others such as VarianceThreshold—with threshold values such as 0.5 as an intermediate value or 0 as a lower limit value—that filter only one or no features at all, respectively. The same applies to the SelectFpr, SelectFdr, and SelectFwe techniques. All of them are based on the use of an alpha —corresponding to the highest uncorrected p-value for features to be kept— which, if left at its default value, only filters out one feature. However, these techniques also fail to improve correlation by filtering fewer features and retaining more information for the model —since there are still features that are redundant or not linked to the outputs among the resulting 30 features.

Finally, it is necessary to discuss the **results in terms of correlation**. In this case, the embedded techniques offer

This article has been accepted for publication in IEEE Transactions on Emerging Topics in Computing. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TETC.2022.3181679

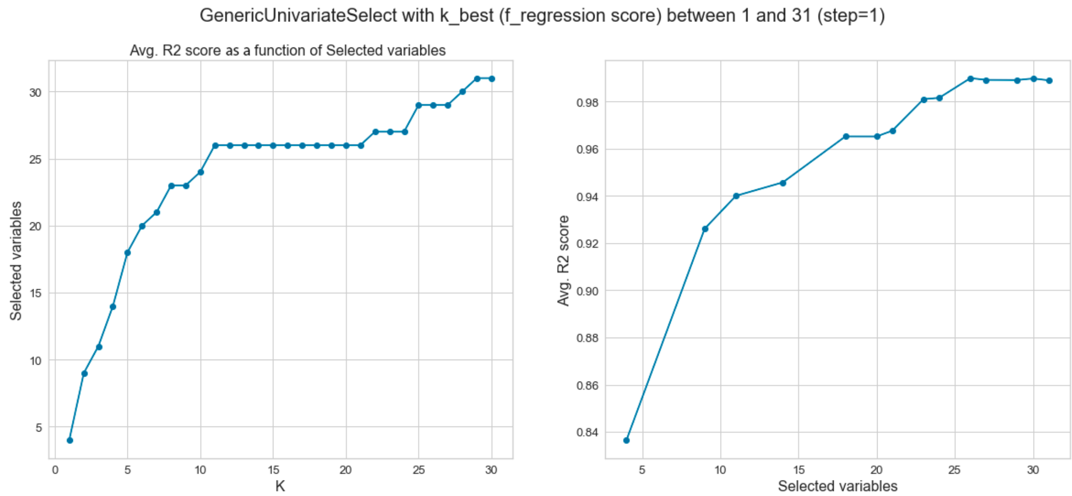


Fig. 1. Number of features selected and R^2 score as a function of the k best selected in GenericUnivariateSelect technique

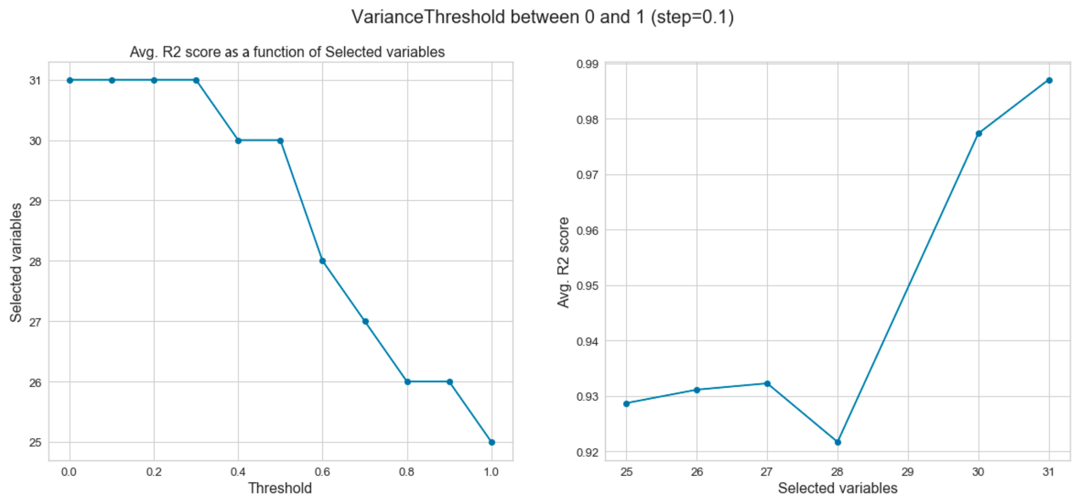


Fig. 2. Number of features selected and R^2 score as a function of the threshold defined in VarianceThreshold technique

more similar results, all achieving a correlation higher than 0.98 (*Avg. R^2 score* column in Table 4). This suggests that they maintain the correlation of the original set of variables, even when considering a smaller number of variables. In the case of the filter methods, the results are similar (*Avg. R^2 score* column in Table 3), although some of the techniques reduce the precision depending on the configuration of the hyperparameters. This is the case of the VarianceThreshold technique when the threshold value is changed from 0 to 0.5 or 0.8. However, even at the risk of lower precision if this particular technique is used, both embedded and filter techniques are successful at filtering features—to a greater degree or lesser degree, as mentioned above—while keeping the original precision close to the ideal value of 1. A correlation of 0.98 or 0.99 is not a decisive factor, both values being very close to the ideal.

As result of the last step (**Step 6**), a series of graphs—one per technique, admitting hyperparameters with values in a finite range—are included to illustrate the relationship between the number of filtered features, the average precision achieved by the models with each selected feature set, and the different techniques and the value obtained by their hyperparameters. These graphs illustrate how the size of the selected feature set changes when the value of any of its hyperparameters is modified within its finite range. It is also possible to appreciate changes in correlation caused by changes in the number of selected features. All these graphs are provided as additional material in the Zenodo repository, inside the "images" folder. In addition, each technique and configuration is linked to its associated graphs in the .XLSX results document. For the sake of brevity, we will only discuss those graphs that we consider to be of greater relevance, since they provide the most easily visually understandable graphs and since they are a significant sample of the different types of hyperparameters that can be configured (such as the thresholds, the number of features to be selected K, or the maximum number of features to be selected).

The first one is that of GenericUnivariateSelect with f_regression as score function. Figure 1 shows the evolution

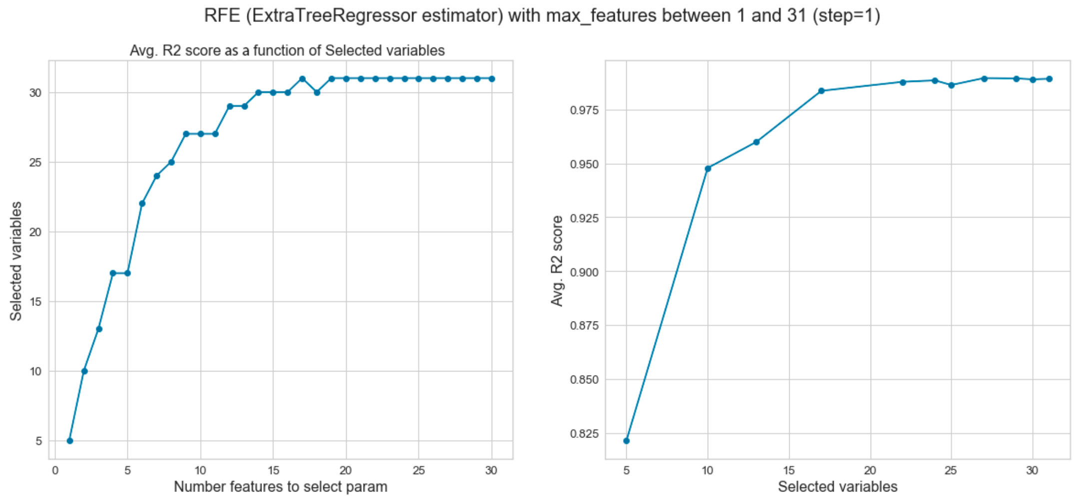


Fig. 3. Number of features selected and R^2 score as a function of the maximum features selected in RFE technique

of the number of features finally selected and average R^2 score for this configuration—taking into account the five models used as estimators during validation—and k best features to be selected as parameter changes. The k best parameter varied in a range from 1 to 31—the total number of features—with an added—i.e., selecting one more feature in each execution. The figure shows how, by selecting one feature per output, a value of 3 features is obtained, with a correlation of almost 0.84. From that point on, correlation increases up to 26 features—especially when k is adjusted to a value of 2 features and selected features increase from 3 to 9. This number of features is obtained by a wide range of k. The figure also shows that the tested models perform better with this number of features than with the original 31, losing correlation when more features are selected.

Among the filter methods, it is also interesting to highlight the VarianceThreshold graph (Figure 2), showing variations as the threshold was changed. After the 0.5 threshold value, the technique begins to filter features. It is interesting to see how far it filters when the entire spectrum of threshold values is tested—from 0.0 to 1.0 with a step of 0.1. The figure shows that, after the 0.4 threshold, it starts to reduce the space of features. In addition, as the threshold increases, the number of features selected decreases. This is expected since by increasing the threshold, the variance of the features that can be selected becomes more restrictive. When the optimum point is reached, it is subjected to the objective pursued during the process of Feature Selection. The 0.0 threshold is obtaining the best correlation but using all features, while 1.0 is obtaining the worst correlation, but with fewer features. Even a middle point, such as the 0.7 threshold—selecting a set of 27 features that provides an increase in correlation with respect to that offered by the 26 or 28 features set offered by other thresholds— can be considered as an optimum point.

Finally, it is also interesting to discuss the graphs corresponding to the embedded RFE method—those that filter out more features. Specifically, Figure 3 shows the evolution of this technique when an Extra Tree Regression model is used as estimator and the maximum number of features to be selected per output is adjusted. In this case, the number of features to be selected is more progressive than in the other techniques. For the first values, the result obtained is very similar to that already yielded by the GenericUnivariateSelect technique in Figure 1. It can also be observed that the optimal correlation point corresponds to 26 features. This number of features is obtained when a maximum number of 8-10 features per output are selected. For any selection higher than 16 features per output the original 31 features are selected—except in the case of 22 features per output when 30 variables are selected. In this case, the R^2 score plot shows that this change slightly improves the precision.

To conclude, it can be argued that the embedded methods select a smaller group of features than the filters, achieving even better correlation on average—at the cost of some of these techniques requiring slightly higher execution times. Almost all embedded techniques filter more features than the best-performing filter method. The most restrictive embedded technique manages to reduce the number of variables to 50% while maintaining correlation above that of some of the filter techniques, such as the variance threshold at 0.8. This last technique only obtains a reduction of approximately 12% and a correlation of 0.92. It is also interesting to indicate that, for filter techniques, the function score *mutual_info_regression* notably increases the time, without improving correlation.

5 Improving Functional Profile Assessments

Taking as a starting point the results obtained in the comparison above, two models have been developed using the features selected by one of the analyzed Feature Selection methods as shown in Figure 4. These models predict the five functional profile scores of the patients considered: one model with higher accuracy—but using more data—, and the other with slightly less accuracy—but using a smaller amount of data.

The creation of two models illustrates the dual potential of Feature Selection techniques. Figure 4 shows the process followed for the creation of the two models and the use for which each model is developed. On the one hand, *Model 1* filters out a smaller number of features while offering better precision. This could be used to measure the functional profile based on the new questionnaires to be fulfilled by health professionals—now with 25 questions instead of 31. This model offers health professionals measurements of the different scores of the functional profile of their aging patients with almost as much precision as the original model, but with fewer questions. On the other hand, *Model 2* filters out a larger number of features (from 31 features to 14), offering slightly less precision. This model could be used by informal caregivers or by the patients themselves to perform periodic self-assessments, thus providing a more constant flow of information on their functional profile. If any irregularities were to be observed whilst applying this model, health professionals could get involved and start using *Model 1* to obtain more accurate measurements.

For the creation of both models, several of the analyzed Feature Selection methods were used rather than just one. First, because each of these models was generated using different methods. Besides, as suggested by researchers such as Chen et al. [26] our models combined filtering and embedded methods. As illustrated in Figure 4, the feature selection phase before the creation of the Machine Learning model has performed in two stages: first a filtering method then an embedded method is applied per model in both stages. This procedure yields better results since the filtering methods applied only filter out the most irrelevant features and the embedded methods used subsequently complete the elimination of features based on the result offered by the first ones.

The filter method used in both models was the GenericUnivariateSelect with an *f_regression* function score and a percentile of 50—since this technique and configuration removes a few features while maintaining the precision of the original set. As an embedded method, in the case of *Model 1* we used the SelectFromModel with the default configuration and RidgeRegression as an estimator. In the comparison, this reduced the feature set to 25 features with an average correlation of 0.992—the highest score of all the tested Machine Learning models. For *Model 2* we used SelectFromModel again with the default configuration but changed the estimator to the Extra Tree Regressor since, in the comparison, it was the one that eliminated the highest number of features.

Finally, as a Machine Learning model for the creation of the prediction model, we applied in both cases Linear Regression—the one offering the best prediction among the five analyzed. As in the comparison, a Linear Regression model was needed for each output. Therefore Scikit-learn's MultiOutputRegressor was used to encapsulate the creation of these five models in a single one. The results obtained in terms of correlation between inputs and outputs and prediction error, using the same dataset as during the comparison, are shown in Table 5.

Metric	Model 1	Model 2
Coefficient of determination (R^2)	0.999661	0.981238
Mean Square Error (MSE)	0.111246	5.772708
Mean Absolute Error (MAE)	0.178976	1.552575

TABLE 5
Results yielded by different models proposed

The results show both models achieve good correlation measured with the R^2 score. However, the error in the predictions, measured with the Mean Square Error (MSE) and Mean Absolute Error (MAE), is higher in the model with fewer features, as expected. The closeness between MSE and MAE values indicates that errors in *Model 1* are of small magnitude—since the MSE tends to give more weight to large errors and to increase its value concerning the MAE when there are many large errors. Moreover, in this case, the MSE has a small value, indicating errors in the order of less than one unit. The MAE value also shows that the mean difference between the actual value of the functional profile scores and the estimator in *Model 1* is very small. Seeing this value and that the functional profile scores oscillate in a range of values between 0 and 100, the error introduced by the model is minimal. This, together with its high precision, confirms the validity of the model to predict the functional profile of aging patients with confidence. On the other hand, *Model 2*'s MAE shows an error of around 1.55 units on average. However, the MSE does show that, in this case, there are situations where the value of the score oscillates

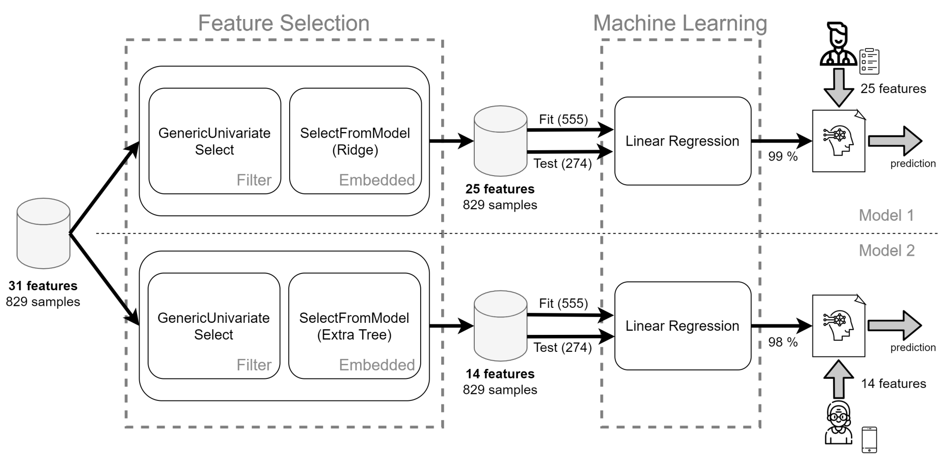


Fig. 4. Proposal for improving functional profile assessments with Feature Selection and Machine Learning

more, producing more significant errors, which penalize this metric compared to that of the MAE. However, the results are positive in both models and adapted to the needs of each one.

Applying a 5-step cross-validation on these models, a mean value of R^2 score of 0.99964 has been obtained for Model 1, with a deviation between the R^2 score obtained in each step of 7.62360x10^{-5}, which shows that the results of the model are reliable, being close to those obtained in the validation with the test set. For Model 2, the results were a mean R^2 score of 0.98166, with a deviation of 4.61616x10^{-3}. This shows that this model is a little less reliable, but still gives very good results to be used as a preventive model.

6 Discussion

We presented a comparison of the different Feature Selection techniques applied to regression problems and showed how the results were applied to the creation of two Machine Learning models for the prediction of the functional profile of older adults. We discuss a few important aspects of our work in this section.

First of all, it is important to note that all the work presented in this paper could be extrapolated to other case studies (within the health or other domains) which require applying Feature Selection on regression problems—i.e., new case studies or other types of health assessments, such as older adults' dementia or loneliness assessments.

Regarding the comparison of the different Feature Selection techniques on regression problems, it has been shown that these techniques are more efficient to reduce the features within a dataset such as the older adults' functional profile. Some techniques can reduce the initial feature set containing 31 features to 25 or even 14—which is particularly relevant since all these features are currently being used in well-validated clinical procedures for the assessment of functional profiles. This stresses the great potential of these techniques for regression problems.

We have also found that the performance of the filter and embedded methods presented theoretically and practically in previous studies for classification problems is maintained when these techniques are applied to regression problems. In general, filter methods achieved less sifting than embedded methods, but with a much better performance in terms of computational time. Execution time was not a challenge for the present case study where all the results, except those of the Yellowbrick RFECV technique, were obtained in the range of tenths/hundredths of seconds for Scikit Learn methods or a few seconds for the case of Yellowbrick methods—due to the fact of being wrapping Scikit Learn methods. Even more considering the reduced capabilities of the computer where the test has been executed. This, however, could be different in other case studies where execution time may be a potential challenge.

Regarding the filtering percentage, the results obtained could act as a reference for the application of Feature Selection techniques on other regression problems. Our comparison could be used to analyze the performance gaps between the different Feature Selection techniques tested. However, it is important to note that we do not recommend extrapolating the filtering percentage as an exact percentage to other case studies [8]. For each case, the filtering percentage will depend on the quality of the initial data set—i.e., the number of irrelevant features or the number of correlated features—of the new case study.

Another important issue to discuss is whether the features that have been retained in the two models are overlapping. That is, whether all the features of the 14-feature model are included as entries in the 25-feature model. In this regard, it has been verified that this is the case. To be more precise about which items of the original 31 have been retained, the 25-feature model has retained 6 of the 10 body functions items, 16 of the 17 body structure items, and 3 of the 4 environmental factors items. The 14-feature model has retained 4, 7 and 3 items from each group, respectively. As can be seen, the first model filters mostly body function items, so these may be the ones with more overlapping information. The second model continues the path filtering a bit more of these items, but mostly filtering body structure items. The least filtered are the environmental factors, filtering only 1 item for both cases.

On the clinical impact implications of eliminating the number of features we eliminated, we have evaluated the amount of time that can be saved on each functional profile assessment with our proposal. Originally, with the 31 items, it took an average of 20 minutes to assess a patient (an average of 38.70 s per item) when the diagnosis was made by an experienced caregiver. The same caregiver now needs an average of 15 minutes for the same diagnosis, through the new version with only 25 questions (improving the average per item to 36 s). As can be seen, from the caregiver's point of view, their process has been optimized by 25%. As for the self-diagnosis by the elder, we have determined that the elders aged 65 to 80 years need 10 minutes on average to fill in the reduced form of 14 questions (an average of 42 s per item) and that the elders aged more than 80 years need 15 minutes (an average of 64 s per item). For that, a reformulation of the question to make them more user-friendly to the elders is needed.

This improvement is due to the fact that the form used by the caregivers has been reduced by almost 20%, from 31 items to 25 items. However, such filtering does not always have to be achieved, and there may be situations where only a small part of the items can be filtered..

Regarding the impact of filtering few features, from the sanitary point of view we can consider two interesting situations. First, if it is more convenient to keep all the features because the time optimization to be achieved is very small and it is better to keep all the information than to obtain that optimization. Second, if it is better to eliminate those few features because they help to optimize the assessment times (even if only a little). What is best in each case is highly subjective, and depends largely on the interpretation of the health professional in charge and the results obtained in the particular case study. In this case, any filtering obtained is interesting, even if it is small. It does not matter too much to lose certain information, since it is not a case study in which a disease that requires great precision in its diagnosis is being detected.

It is also relevant to discuss the application of these Feature Selection techniques to the assessment of functional profiles. Two Machine Learning models were created to

This article has been accepted for publication in IEEE Transactions on Emerging Topics in Computing. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TETC.2022.3181679

establish the functional profile scores using fewer data. Both the model that selected a smaller number of features and the model that selected a larger number yielded correlation between inputs and outputs close to 100%. For *Model 1*, the error included was so slight that it could be considered negligible. Therefore, the values yielded by this model are as accurate as those provided by the original features set. For the *Model 2*, the error is still not very significant: 1.55 units on average, with some cases where it is slightly more pronounced. As suggested above, this could be used as a preventive model used by informal caregivers to quickly obtain more frequent, approximate functional scores. In case the scores suggest a possible problem, health professionals could then apply the more accurate model.

Our results suggest novel possibilities for the assessment of the functional profile of older adults—one of the most costly issues in terms of human healthcare resources, given that loss of functionality is an inherent consequence of aging. With this proposal, informal caregivers can continuously measure their patients' functional profiles changes, with two advantages: on the one hand, health professionals have to perform fewer assessments while their patients' functional profiles can be continuously monitored. In addition, the assessments performed by health professionals would be faster and more efficient, since fewer parameters would be assessed to obtain the same results. This would benefit healthcare systems, by freeing up time that could be devoted to providing better care. Therefore, the objective of this paper has been achieved and it can be considered a declaration that Feature Selection on regression problems can be employed as the technological tool that can improve the assessment of health pathologies and conditions.

7 RELATED WORK

Dimensionality Reduction (DR) techniques have become very important in Data Science due to the huge amount of data generated every day in the so-called Big Data era [19]—with more and more works applying these techniques to different domains.

Health care is one of the fields where the use of these techniques is imperative. Feature dimension is one of the main challenges in the analysis of healthcare data [9], [12], [32]. Medical tests often generate significant amounts of data [33]—input variables or features—which are difficult to analyze directly by using Data Mining techniques such as Machine Learning or Deep Learning. Thus, proposals such as that of Lee et al. [12] suggested the use of DR techniques to analyze Electronic Medical Records (EMR). They argued that these records were usually composed of hundreds to thousands of medical variables, causing a problem of data high-dimensionality—the so-called curse of dimensionality [21].

Within DR techniques, two types of approaches can be established [12]: Feature Extraction and Feature Selection. Both approaches are not mutually exclusive and are often used together [34]. Feature Extraction methods aim to extract a series of new features from existing features in a dataset. These new features will be more expressive than the original ones, thus allowing a better analysis of the data. This is the approach followed by proposals such as one of Nuñez-Godoy et al. [35], who employ Feature Extraction's Principal Component Analysis (PCA) algorithm to reduce the high-dimensionality of sensor-gathered data to detect patterns in human-sitting-poses. The application of these techniques helps improve the results yielded by the initial prediction models, using the original feature set, while reducing the computational cost. However, the use of these techniques still implies collecting the same number of input variables, so they do not provide a solution—or, at least, not by themselves—to the problem addressed in this paper.

On the other hand, Feature Selection techniques aim to directly reduce the set of features to be collected as input. This way, not only do they improve the performance of prediction models [8]—both in terms of accuracy and computational costs—they also help analyze the features that are collected. Their analytical potential results in several advantages, such as a better understanding of the problem. The Feature Selection process helps eliminate features that are redundant or have no real relation to the output—even if, a priori, healthcare professionals believe that they do.

For these reasons, these types of techniques have been widely used for years. Neumann et al. [36] presented some continuous Feature Selection approaches, measuring their performance in different health datasets. Wei and Billings [37] developed a new unsupervised forward orthogonal search (FOS) for Feature Selection and applied it to different health datasets from the UCI Machine Learning Repository. Maldonado et al. [38] proposed a wrapper method based on the use of kernel functions with Support Vector Machines for classification problems. They compared their method with other existing ones using different datasets, including the Colorectal Microarray (CRMA) and the Wisconsin Breast Cancer (WBC) datasets. Huang et al. [2] applied a filter-based method to an antidepressant medication utilization study, discussing the advantages of this method with respect to a wrapper method on logistic regression. Genuer et al. [39] proposed the use of random forests in wrapper Feature Selection techniques, applying them on four different classification datasets, corresponding to Colon, Leukemia, Lymphoma, and Prostate diseases, and providing some experimental metrics. Jeanneret et al. [40] performed a chemistry-driven Feature Selection in order to analyze urine samples corresponding to dioxin intoxication. Javed et al. [41] demonstrate the performance of filter methods on three different datasets belonging to binary classification (two-class) problems, among them a drug discovery and a heart disease classification dataset. Cateni et al. [42] proposed the combination of different Feature Selection techniques in a two-phase procedure: first using filter methods and then an exhaustive search. This proposal was validated on several UCI datasets, among others. Bodur and Douglas [14] developed and tested a filter algorithm for Feature Selection in healthcare datasets. Uphade et al. [43] make use of these techniques also in classification problems to try to detect which factors should be taken into account in covid patients to try to place them in a range of days necessary for their recovery. Bommert et al. [44] compare the use of different filter methods to select the most relevant features in gene expression within bioinformatics. They focus on this type of methods because they are more computationally efficient

This article has been accepted for publication in IEEE Transactions on Emerging Topics in Computing. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TETC.2022.3181679

than wrappers, being a better choice for high-dimensional data such as the 14 datasets used for the comparison. Outside of the health domain, Guo et al. [45] proposed a method to perform regression feature selection with noised data —or data with outliers— when the distribution of representation error is unknown. Degeest et al. [46] discuss the importance of Feature Selection as a preprocessing step in Machine Learning, highlighting the relevance of filter methods and centering in the context of regression problems.

While some proposals offer new Feature Selection algorithms, others delve into the existing ones and their use in the health domain. Remeseiro and Bolon-Canedo [47] reviewed the Feature Selection techniques in medical applications. Suresh et al. [13] defined a full process, beginning with data cleansing and outlier detection, following with dimension reduction using SVM-RFE, and ending with the evaluation of results on the RFS-SVM algorithm and other traditional classifiers. They applied this process on a Prima Indian diabetes dataset. Chen et al. [26] proposed the use of ensemble methods for Feature Selection on health data, consisting of the use of filter, wrapper, and embedded methods together. Chicco and Oneto [16] showed in their research that machine learning could be used to predict sepsis shock, as well as demonstrating that Feature Selection could be employed to identify unexpected symptoms and relevant clinical components of septic shock. Xu et al. [48] proposed a general framework that, using global redundancy minimization in orthogonal regression, emphasized the importance of the correlation between features in the Feature Selection processes. Ali et al. [49] use this type of techniques to enable the creation of Machine Learning models capable of predicting drug response according to omics profiles in precision oncology applications.

In addition, proposals such as that of Arowolo et al. [34] employed these techniques to select the most relevant features within a dataset, before employing Feature Extraction techniques to improve the accuracy of prediction models. This approach was used to analyze in a more efficient way data from the Malaria Vector Gene Expression. Other proposals such as that of Murthy [50] employed the two techniques in a reverse process: first new features were generated with Feature Extraction and then the original features plus the new ones were filtered with Feature Selection. The framework they defined for this is called Minimum Projection error Minimum Redundancy (MPeMR).

However, most applications of Feature Selection are linked to classification problems—aiming to predict to which discrete class from within a dataset a sample belongs, based on a set of inputs. When the expected output is a continuous value—i.e., a regression problem—the number of proposals available in the literature is much smaller. Of the above-mentioned papers, only that of Chicco and Oneto [16] uses Feature Selection on regression problems with health data—ignoring previously published methods, such as that of Huang et al. [2]. Outside the health domain, examples are scarce. Javidi et al. [17] proposed a new Feature Selection technique on regression problems based on the use of the Biology Migration Algorithm (BMA) for Feature Selection and game theory for feature clustering. To test its efficiency, its authors evaluated it on several datasets from different domains belonging to regression problems.

Furthermore, as far as the authors know, no works have reviewed Feature Selection techniques applied to regression problems and compared their performance on a specific case study. For example, Chandrashekar [8] reviews Feature Selection techniques applied to classification problems, offering a comparison of their performance on different health datasets. El Aboudi et al. [25] also provide an overview of different Feature Selection techniques on classification problems, focusing on wrapper methods. Finally, Remeseiro et al. [47] discuss the importance of Feature Selection on medical applications, highlighting the high number of regression problems existing in this domain. However, their techniques' comparison only covers classification problems' datasets.

Finally, our work includes also Machine Learning and Deep Learning tasks. Since there are many Machine Learning algorithms for the definition of prediction models in regression problems, the existing literature was reviewed. Following the recommendations of Jolly et al. [30], tests were conducted on the most common algorithms—linear regression, logistic regression, support vector machines, and tree-based algorithms. Despite using Deep Learning, a Multi-Layer Perceptron Network (MLP) was chosen. Our choice of the most suitable neural network is based on the study by Bhavya and Pillai [10], which discusses the suitability of several neural network types for the analysis of healthcare data.

8 Conclusions and Future Work

This paper aimed to reduce the number of parameters that health professionals must consider to assess an older adult. Feature Selection techniques were used to reduce an initial set of features into a smaller subset containing the relevant information from the initial set while eliminating redundant features.

We created two different Machine Learning models using reduced sets of features to predict functional profile scores: one using fewer features that lose some reliability; and another using more features but with higher reliability. Both models could be used together—one as a preventive model so that the patient can be constantly monitored, and the other to be used only by health professionals. The input features used in each model were obtained by using Feature Selection. For this purpose, an initial comparison of different techniques and configurations was carried out, taking into account the computational time taken in selection, the number of features selected, and the level of correlation between inputs and outputs achieved.

We argue that the use of Feature Selection techniques in the healthcare domain is feasible when working on a regression problem since it can improve the results and help health professionals in performing assessments. We also argue that they can be used in situations where accuracy is very high—close to 100%—but it is necessary to reduce the number of collected variables. This paper does not aim to demonstrate that better predictions are obtained with fewer variables after using Feature Selection. Rather, it shows that predictions of the same quality can be obtained with fewer variables. This should help improve the sustainability of healthcare systems—saving resources and time, which can be then spent on more pressing tasks. Additionally, the comparison provided serves as a starting point for future work seeking to employ these techniques through implementations already available in the most widely used Data Science tools.

The data employed in this paper was taken from the MIAPe platform which collects assessment data of older adults living in assisted living facilities and nursing homes, including functional profile data.

As future work, one important topic is to include wrappers methods into the evaluation, since space constraints have not allowed us to include them in this study. As well, we will aim to create a framework that allows health professionals to interact with the algorithms or feature selection techniques to filter and reduce the features. In this way, they will be able to eliminate features manually based on recommendations, checking how the accuracy of the models is altered. This would allow the model to adapt better to the real needs of healthcare professionals. It would also help to resolve the uncertainties left by the automatic application of Feature Selection. To do this, we could include in the Feature Selection process those techniques tested in the comparison that generated visual results to show correlations, mutual information, and other issues of interest to the users when they filter features.

The need for a flexible and interactive framework such as the one mentioned above is clear since the automatic techniques do not integrate critical domain knowledge or take into account how complicated it can be to establish the value of a specific feature. For instance, they do not consider the relationship that might exist between two features when collecting their values—i.e., the value of two features can be obtained jointly, and it might be interesting to keep both despite one of them providing little information about what is being diagnosed. They do not consider either the importance that a specific feature might have to link the diagnosis of a disease with another one. All these issues could be avoided if users were in the loop of the Feature Selection process.

ACKNOWLEDGMENTS

This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), the FPU19/03965 grant, the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and the European Regional Development Fund.

REFERENCES

[1] J. R. Gonçalves, I. Ramalhinho, B. L. Sleath, M. J. Lopes, and A. M. Cavaco, "Probing pharmacists' interventions in long-term care: a systematic review," *European geriatric medicine*, pp. 1–21, 2021.

[2] S. H. Huang, L. R. Wulsin, H. Li, and J. Guo, "Dimensionality reduction for knowledge discovery in medical claims database: Application to antidepressant medication utilization study," *Computer Methods and Programs in Biomedicine*, vol. 93, no. 2, pp. 115–123, feb 2009.

[3] D. Kalra, "Electronic health record standards," 2006.

[4] E. Moguel, J. Berrocal, J. M. Murillo, J. García-Alonso, D. Mendes, C. Fonseca, and M. Lopes, "Enriched elderly virtual profiles by means of a multidimensional integrated assessment platform," in *Procedia Computer Science*, vol. 138. Elsevier B.V., jan 2018, pp. 56–63.

[5] C. M. Bell, S. S. Araki, and P. J. Neumann, "The association between caregiver burden and caregiver health-related quality of life in alzheimer disease," *Alzheimer Disease & Associated Disorders*, vol. 15, no. 3, pp. 129–136, 2001.

[6] C. Silveira, R. T. Souza, M. L. Costa, M. A. Parpinelli, R. C. Pacagnella, E. C. Ferreira, J. Mayrink, J. P. Guida, M. H. Sousa, L. Say *et al.*, "Validation of the who disability assessment schedule (whodas 2.0) 12-item tool against the 36-item version for measuring functioning and disability associated with pregnancy and history of severe maternal morbidity," *International Journal of Gynecology & Obstetrics*, vol. 141, pp. 39–47, 2018.

[7] S. H. Park, E. A. Demetriou, K. L. Pepper, Y. J. C. Song, E. E. Thomas, I. B. Hickie, N. Glozier, and A. J. Guastella, "Validation of the 36-item and 12-item self-report world health organization disability assessment schedule ii (whodas-ii) in individuals with autism spectrum disorder," *Autism Research*, vol. 12, no. 7, pp. 1101–1111, 2019.

[8] G. Chandrashekar and F. Sahin, "A survey on feature selection methods," *Computers and Electrical Engineering*, vol. 40, no. 1, pp. 16–28, jan 2014.

[9] S. Itani, F. Lecron, and P. Fortemps, "Specifics of medical data mining for diagnosis aid: A survey," pp. 300–314, mar 2019.

[10] S. Bhavya and A. S. Pillai, "Prediction models in healthcare using deep learning," in *Advances in Intelligent Systems and Computing*, vol. 1182 AISC. Springer, dec 2021, pp. 195–204.

[11] J. Rojo, E. Moguel, C. J. Fonseca, M. Lopes, J. G. Alonso, and J. Hernández, "Time series forecasting to predict the evolution of the functional profile of the elderly persons," in *Gerontechnology III: Contributions to the Third International Workshop on Gerontechnology, IWoG 2020, October 5-6, 2020, Évora, Portugal*. Springer, 2021, pp. 11–22.

[12] C. Lee, Z. Luo, K. Y. Ngiam, M. Zhang, K. Zheng, G. Chen, B. C. Ooi, and W. L. J. Yip, "Big Healthcare Data Analytics: Challenges and Applications." Springer, Cham, 2017, pp. 11–41. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-58280-1{_}2

[13] A. Suresh, R. Kumar, and R. Varatharajan, "Health care data analysis using evolutionary algorithm," *Journal of Supercomputing*, vol. 76, no. 6, pp. 4262–4271, jun 2020. [Online]. Available: https://doi.org/10.1007/s11227-018-2302-0

[14] Bodur and Atsa'am, "Filter Variable Selection Algorithm Using Risk Ratios for Dimensionality Reduction of Healthcare Data for Classification," *Processes*, vol. 7, no. 4, p. 222, apr 2019. [Online]. Available: https://www.mdpi.com/2227-9717/7/4/222

[15] J. G. Dy and C. E. Brodley, "Feature Selection for Unsupervised Learning," Tech. Rep., 2004.

[16] D. Chicco and L. Oneto, "Data analytics and clinical feature ranking of medical records of patients with sepsis," *BioData Mining*, vol. 14, no. 1, dec 2021.

[17] M. M. Javidi, "Feature selection schema based on game theory and biology migration algorithm for regression problems," *International Journal of Machine Learning and Cybernetics*, vol. 12, no. 2, pp. 303–342, feb 2021.

[18] R. F. Xu and S. J. Lee, "Dimensionality reduction by feature clustering for regression problems," *Information Sciences*, vol. 299, pp. 42–57, apr 2015.

[19] G. T. Reddy, M. P. K. Reddy, K. Lakshmanna, R. Kaluri, D. S. Rajput, G. Srivastava, and T. Baker, "Analysis of dimensionality reduction techniques on big data," *IEEE Access*, vol. 8, pp. 54 776–54 788, 2020.

[20] L. Van Der Maaten, E. Postma, and J. Van den Herik, "Dimensionality reduction: a comparative," *J Mach Learn Res*, vol. 10, no. 66-71, p. 13, 2009.

[21] F. Y. Kuo and I. H. Sloan, "Lifting the curse of dimensionality," *Notices of the AMS*, vol. 52, no. 11, pp. 1320–1328, 2005.

[22] B. Venkatesh and J. Anuradha, "A review of feature selection and its methods," *Cybernetics and Information Technologies*, vol. 19, no. 1, pp. 3–26, 2019.

[23] G. Wei, J. Zhao, Y. Feng, A. He, and J. Yu, "A novel hybrid feature selection method based on dynamic feature importance," *Applied Soft Computing*, vol. 93, p. 106337, 2020.

[24] E. Alpaydin, *Introduction to machine learning*. MIT press, 2020.

[25] N. El Aboudi and L. Benhlima, "Review on wrapper feature selection approaches," in *Proceedings - 2016 International Conference on Engineering and MIS, ICEMIS 2016*. Institute of Electrical and Electronics Engineers Inc., nov 2016.

[26] C. W. Chen, Y. H. Tsai, F. R. Chang, and W. C. Lin, "Ensemble feature selection in medical datasets: Combining filter, wrapper, and embedded feature selection results," *Expert Systems*, vol. 37, no. 5, p. e12553, oct 2020. [Online]. Available: https://doi.org/10.1111/exsy.12553

[27] C. Fonseca, M. Lopes, D. Mendes, P. Parreira, L. Mónico, and C. Marques, "Psychometric properties of the elderly nursing core set," in *International Workshop on Gerontechnology*. Springer, 2018, pp. 143–153.

[28] M. J. Lopes and C. Fonseca, "Processo de construçao do elderly nursing core set," *Journal of Aging & Inovation*, vol. 2, no. 1, pp. 121–131, 2013.

[29] W. H. Organization *et al.*, "Ifc: International classification of functioning, disability and health," 2001.

[30] K. Jolly, *Machine Learning with scikit-learn Quick Start Guide: Classification, regression, and clustering techniques in Python*. Packt Publishing Ltd, 2018.

[31] "sklearn.metrics.r2score | scikit−learn 1.0.2 documentation." [Online]. Available: https://scikit-learn.org/stable/modules/generated/sklearn.metrics.r2_score.html

[32] J. Rojo, J. Hernandez, and J. M. Murillo, "A Personal Health Trajectory API: Addressing Problems in Health Institution-Oriented Systems," *Lecture Notes in Computer Science*, vol. 12128, pp. 519–524, 2020. [Online]. Available: http://link.springer.com/10.1007/978-3-030-50578-3{_}37

[33] J. Rojo, J. Hernandez, J. M. Murillo, and J. Garcia-Alonso, "Blockchains' federation for integrating distributed health data using a patient-centered approach," mar 2021. [Online]. Available: http://arxiv.org/abs/2103.05406

[34] M. O. Arowolo, M. O. Adebiyi, A. A. Adebiyi, and O. J. Okesola, "A Hybrid Heuristic Dimensionality Reduction Methods for Classifying Malaria Vector Gene Expression Data," *IEEE Access*, vol. 8, pp. 182 422–182 430, oct 2020.

[35] S. Nunez-Godoy, V. Alvear-Puertas, S. Realpe-Godoy, E. Pujota-Cuascota, H. Farinango-Endara, I. Navarrete-Insuasti, F. Vaca-Chapi, P. Rosero-Montalvo, and D. H. Peluffo, "Human-sitting-pose detection using data classification and dimensionality reduction," in *2016 IEEE Ecuador Technical Chapters Meeting (ETCM)*. IEEE, oct 2016, pp. 1–5. [Online]. Available: http://ieeexplore.ieee.org/document/7750822/

[36] J. Neumann, C. Schnörr, and G. Steidl, "Combined SVM-based feature selection and classification," *Machine Learning*, vol. 61, no. 1-3, pp. 129–150, nov 2005. [Online]. Available: https://link.springer.com/article/10.1007/s10994-005-1505-9

[37] H. L. Wei and S. A. Billings, "Feature subset selection and ranking for data dimensionality reduction," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 29, no. 1, pp. 162–166, jan 2007.

[38] S. Maldonado and R. Weber, "A wrapper method for feature selection using Support Vector Machines," *Information Sciences*, vol. 179, no. 13, pp. 2208–2217, jun 2009.

[39] R. Genuer, J.-M. Poggi, and C. Tuleau-Malot, "Variable selection using random forests," *Pattern Recognition Letters*, vol. 31, no. 14, pp. 2225–2236, oct 2010. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0167865510000954

[40] F. Jeanneret, J. Boccard, F. Badoud, O. Sorg, D. Tonoli, D. Pelclova, S. Vlckova, D. N. Rutledge, C. F. Samer, D. Hochstrasser, J.-H. Saurat, and S. Rudaz, "Human urinary biomarkers of dioxin exposure: Analysis by metabolomics and biologically driven data dimensionality reduction," *Toxicology Letters*, vol. 230, no. 2, pp. 234–243, oct 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S037842741301374X

[41] K. Javed, H. A. Babri, and M. Saeed, "Impact of a metric of association between two variables on performance of filters for binary data," *Neurocomputing*, vol. 143, pp. 248–260, nov 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0925231214007358

[42] S. Cateni, V. Colla, and M. Vannucci, "A Hybrid Feature Selection Method for Classification Purposes," in *2014 European Modelling Symposium*. IEEE, oct 2014, pp. 39–44. [Online]. Available: http://ieeexplore.ieee.org/document/7153972/

[43] D. Uphade and A. Muley, "Identification of parameters for classification of covid-19 patient's recovery days using machine learning techniques," *J. Math. Comput. Sci.*, vol. 12, pp. Article–ID, 2022.

[44] A. Bommert, T. Welchowski, M. Schmid, and J. Rahnenführer, "Benchmark of filter methods for feature selection in high-dimensional gene expression survival data," *Briefings in Bioinformatics*, vol. 23, no. 1, p. bbab354, 2022.

[45] Y. Guo, W. Wang, and X. Wang, "A robust linear regression feature selection method for data sets with unknown noise," *IEEE Transactions on Knowledge and Data Engineering*, 2021.

[46] A. Degeest, B. Frénay, and M. Verleysen, "Reading grid for feature selection relevance criteria in regression," *Pattern Recognition Letters*, vol. 148, pp. 92–99, 2021.

[47] B. Remeseiro and V. Bolon-Canedo, "A review of feature selection methods in medical applications," p. 103375, sep 2019.

[48] X. Xu, X. Wu, F. Wei, W. Zhong, and F. Nie, "A general framework for feature selection under orthogonal regression with global redundancy minimization," *IEEE Transactions on Knowledge and Data Engineering*, 2021.

[49] M. Ali and T. Aittokallio, "Machine learning and feature selection for drug response prediction in precision oncology applications," *Biophysical reviews*, vol. 11, no. 1, pp. 31–39, 2019.

[50] C. A. Murthy, "Bridging Feature Selection and Extraction: Compound Feature Generation," *IEEE Transactions on Knowledge and Data Engineering*, vol. 29, no. 4, pp. 757–770, apr 2017.

Javier Rojo is a PhD student and research fellow at the University of Extremadura, Spain, through a grant for the formation of university professors from the Spanish Ministry of Science, Innovation, and Universities. He obtained his MSc. in Computer Science from the University of Extremadura in 2021. His research interests include software engineering, eHealth, pervasive computing, mobile computing, and gerontechnology.

Lara Guedes de Pinho is a Researcher at the University of Évora and the Comprehensive Health Research Centre (CHRC). She obtained a PhD in Nursing and Health from the University Rovira i Virgili, Spain, in 2021 and a PhD in Psychology from the University of Aveiro, Portugal, in 2018. Her research interests include aging, eHealth, functioning and mental health.

César Fonseca completed his PhD in Nursing at the University of Lisbon, Portugal. He is currently Professor at the University of Évora, and researcher at the Comprehensive Health Research Center (CHRC) - Research, Education, Training and Innovation in Clinical research and Public Health – Universidade Nova de Lisboa.

Manuel José Lopes is a Full Professor at the Nursing School of the University of Évora, Portugal, and a researcher at the Comprehensive Health Research Centre (CHRC). His research interests are aging and functionality, and models of care.

Sumi Helal is a Full Professor at the University of Florida, USA, and Director of its Mobile and Pervasive Computing Laboratory. His areas of research span Digital Health and the Internet-of-Things with applications to active and healthy living and aging, assistive environments (e.g., smart homes) and independent living. Professor Helal is a Boilermaker (Ph.D., Purdue University, class of 1991), Fellow of the IEEE, Fellow of the AAAS, Fellow of the IET, and a member of Academia Europaea.

Juan Hernández obtained a PhD degree in Computer Science at the Technical University of Madrid, Spain, in 1995. He is currently a Full Professor at the University of Extremadura, Spain, and the Head of the Quercus Software Engineering Group. His research interests include service-oriented computing, ambient intelligence, and model-driven development.

Jose Garcia-Alonso is an Associate Professor at the University of Extremadura, Spain, where he complete his PhD in software engineering in 2014. He is the co-founder of Gloin, a software consulting company, and Health and Aging Tech, an eHealth company. His interests include software engineering, mobile computing, pervasive computing, eHealth, and gerontechnology.

Juan M. Murillo is Full Professor at the University of Extremadura, Spain, and co-founder of the start-up Gloin. His research interests include software architectures, Pervasive and Mobile Computing and Quantum Computing. Murillo holds a PhD in computer science from the University of Extremadura.

Part III

Final Remarks

Chapter 8

Conclusions and Future Work

Contents

Great knowledge gives rise to great doubts

Aristotle

This chapter concludes the dissertation. Section 8.1 presents a discussion of the results obtained and presented in Chapter 2. These results are linked to the objectives of the dissertation presented in Chapter 1, indicating whether they have been fulfilled or not. In Section 8.2 the limitations found in this dissertation are presented after their analysis for discussion. Section 8.3 presents the general conclusions of the Ph.D. Finally, Section 8.4 introduces some future lines of work with which to continue advancing in the line of research presented in this dissertation.

8.1 Discussion

Once all the results obtained throughout this dissertation and the work done has been presented, a brief discussion of them is pending. With this, it is intended to check if the objectives set in this dissertation have been achieved and if the hypotheses have been validated or if any of them should be refuted.

In the area of the inclusion of IoT and IoMT devices as part of the Personal Health Trajectory, different proposals have been defined that have allowed these devices to be used by users who are not very familiar with them, such as aging adults. In addition, these proposals have also been applied to rural environments, and proposals have even been developed to collect health data that was not previously possible to collect, such as medication intake. All this information is ready to be integrated into the raw Personal Health Trajectory, but also to generate new information through process mining, which can be even more useful for the Personal Health Trajectory than the raw information from the devices. With all this, the general objective GO3 (*Integrate data flow from IoMT/IoT devices with healthcare information systems*) can be considered as completed, as well as the specific objective SO6 (*Apply process mining algorithms to filter information from the constant data stream of IoT/IoMT devices*).

Regarding the implementation of these proposals in real environments, there are different aspects that may affect them. For example, in the case of proposals to automate interactions with IoT devices, these proposals are subject to the success of previous proposals in the literature on the interoperability of heterogeneous IoT devices. If these proposals are ultimately unsuccessful, the automation proposals would limit their use to creating models that could only take into account, for example, devices from the same manufacturer using the same communication protocol. Likewise, the implementation of the proposal to create Smart Nursing Homes could be problematic in several ways, including the maintenance of the architecture in an environment where there are no specialists in intelligent devices that can maintain the entire infrastructure in case of failure. Also, the type of devices that may exist in a nursing home could create interference that could affect the smart devices, affecting the operation of the proposal.

The health data integration proposals have achieved the specific objectives GO1 (*Provide a framework, with an associated development methodology, for accessing the health trajectory data of an individual*) and GO2 (*Unify health information systems to achieve PHT for patients*), as well as the specific objectives SO1 (*Implement an interface or API to provide access to the data in our framework*), SO4 (*Standardize proprietary information system technology data, through the use of interfaces, such as REST*) and SO5 (*Use blockchain,* *and specifically the concept of blockchain federation, to achieve integration of a user's health data*). For this purpose, a couple of proposals have been mainly used: the proposal of interoperability of distributed data through the concept of blockchains' federation and the proposal of Personal Health Trajectory Traceability. Moreover, it can be considered that the indicated objectives have been achieved with only the first proposal, being the results of the second proposal an addition that contributes to improving the overall result of the dissertation beyond the limits set at the beginning.

These proposals mainly face the problem that their implementation may be controversial in terms of patient data privacy. These proposals need for sharing patient data across health systems. People's willingness to share their health data depends largely on how useful they see this in improving public health, as well as the nature of the data being shared. This can greatly condition people's acceptance of sharing their data. However, our proposal allows determining which data is going to be shared in the Personal Health Trajectory and which is not, making it easier to limit their application to another type of information. As well, patients must understand that this generates benefits for them and for society in general and that this is safe since nothing will be shared that they do not accept.

As long as data protection regulations are complied with and the patient's approval is obtained, the sharing of her data will be done in benefit to her. In addition to the fact that the data sharing will be done in a controlled environment, with the parties having access to the shared data being known and the patient being aware of it. Likewise, if a patient does not wish to share her data, it will be sufficient not to have her blockchain generating her Personal Health Trajectory. The rest of the patients who do want to share their data will still be able to have their blockchains and receive the benefits of the proposal.

Needless to say, these proposals could be applied to generate trajectories for users with not only health data, but any type of data. Even trajectories where the center is not a user, but another type of actor, such as an organization, institution, or service. This would allow any institution to have its data interoperable. Examples of this could be the integration of banking data, in banks operating in different countries, or even of users operating with different banks; or the integration of the data of a user who uses different cloud storage systems to manage their files.

Finally, the proposals for enriching and improving the interpretability of the data have enabled us to cover the rest of the objectives that remained to be completed. Specifically, these objectives are the general objective GO4 (*Enrich and interpret patient data after integrating it from different sources*) and the specific objectives SO2 (*Apply data mining algorithms to enrich the knowledge* *provided by a patient's health trajectory data*) and SO3 (*Apply feature selection algorithms to determine which data are most relevant to a diagnosis from the entire integrated data*). Of the latter, the proposal to test the feasibility of using the Personal Health Trajectory for forecasting patient evolution covers SO2, while the Feature Selection proposals cover SO3. The proposals for the use of quantum computing as services are outside these two specific objectives, but they do contribute to improving the results obtained as part of the general objective GO4.

The use of data mining techniques in the Personal Health Trajectory is so broad that it is difficult to define the number of proposals that could arise along these lines. The work carried out has served to demonstrate that new types of analysis are possible thanks to the Personal Health Trajectory and to encourage new authors to continue working on this. Likewise, the case study to which Feature Selection techniques have been applied has helped to demonstrate that the use of these techniques is viable in health problems and that they can respond to new objectives, such as optimizing data collection in health processes (beyond the optimization of prediction models, which is what is usually pursued by the application of Feature Selection). However, it is unthinkable to try to limit all the cases of study to which this proposal can be applied. For this reason, a methodology is defined and offered so that any researcher can apply it to his or her case studies. For their part, the quantum computing proposals open the way to the creation of quantum services of any kind, and not only for the analysis of health data. This will contribute in the future to creating more efficient computing ecosystems, where both models of computing coexist, each performing the tasks for which each type of computing offers the best performance.

Finally, it should be noted that, in addition to what is discussed here, all the articles where each of the results of this dissertation have been presented have a discussion section where aspects related to each of the proposals are discussed in more detail.

Figure 8.1 shows the actual implementation of the architecture presented in Figure 1.3 of Chapter 1. As can be seen, the different proposals that have been made during this dissertation have been placed in the part of the architecture they covered. In the inclusion of data from devices, proposals have been created to automate the actions and extract relevant information from them. As shown in the figure, these proposals can be used independently or together. Whether these proposals are used or not, data from devices end up integrated with data from healthcare institutions through the blockchains' federation proposal. On top of this, the proposals of data mining to forecast the future of the patient and feature selection to select the determinants of each pathology are applied. All this data, together with the raw data integrated into the blockchain. In addition, you can see how the Personal Health Trajectory API layer has ended up being more complex than expected. In addition to the FedBlocks Connector API that provided coverage for that API to be developed, the Personal Health Trajectory Traceability layer has been developed on top of it. This PHT Traceability makes use of the FedBlocks Connector API to obtain traceability and provides a new API on top of it to replace it. This API includes everything from the previous one in addition to new health traceability functionalities. Quantum computing proposals are left out of this architecture because it does not add functionality to the Personal Health Trajectory architecture, but offer an alternative form of computing for the proposals in the *Layer III. Personal Health Trajectory.*

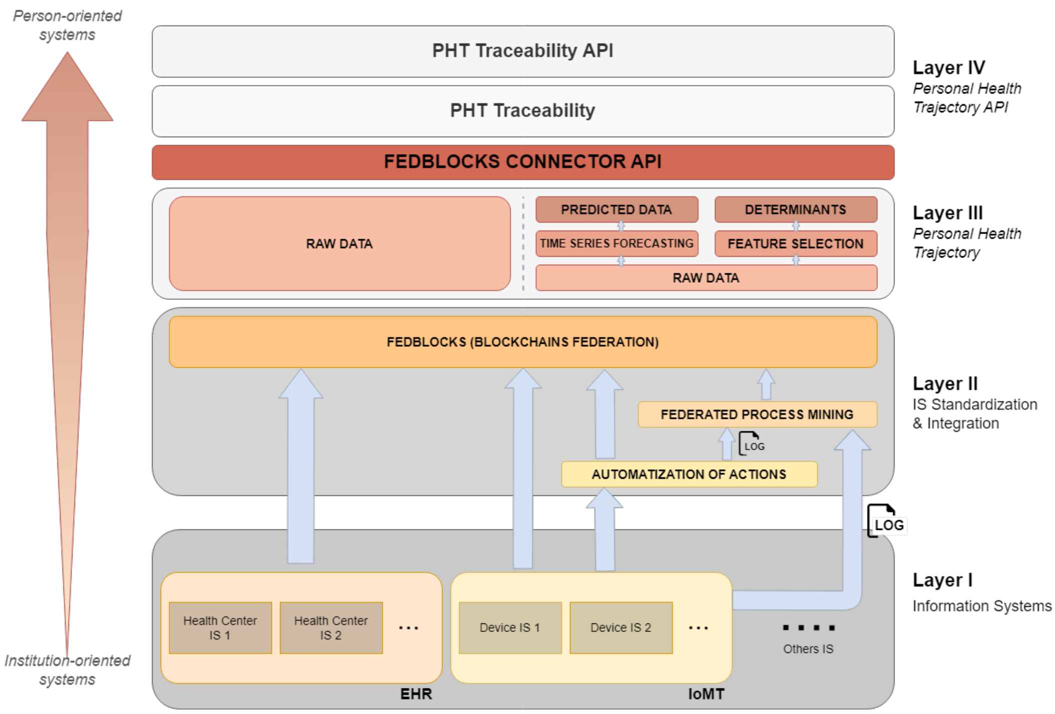


Figure 8.1: Architecture implemented for the Personal Health Trajectory Framework

Regarding the validation or refutation of the hypotheses, we can say that the first of the hypotheses *"H1. The incorporation of the concept of Personal Health Trajectory in the field of eHealth is going to allow building better health systems"* is being validated through the implementation of the solutions of this dissertation in a platform named above and used by 50 sociosanitary institutions from which the data for the case studies of many of the investigations carried out have been taken: MIAPe. The second hypothesis is *"H2.*

The integration of data from IoT/IoMT devices along with EHRs in healthcare systems is going to enable a more accurate understanding of a person's health over time". It has been validated through the proposals of health data integration and the review of different literature sources that confirm this. The third and last hypothesis *"H3. The enrichment and improvement of the interpretability of integrated data from different sources will make it possible to find relationships between data that were not previously contemplated"* has been demonstrated with the proposals of patient evolution forecasting and Feature Selection proposals.

8.2 Limitations

Talking about the principal limitations of our thesis

All of these proposals are not free of discussion and, although they have achieved their objectives, each of them has its own limitations. Some of these limitations are specific to each proposal, and have already been mentioned in the discussion section (Section 8.1). Others are more general and affect the overall outcome of the dissertation:

- *Connection between heterogeneous IoT devices.* The automation proposals [4, 5, 87] are subject to being able to interconnect heterogeneous IoT devices, from different manufacturers, that follow different communication protocols. Although this problem is already being solved by other existing proposals in the literature [84], the success of the proposals in this dissertation depends on the success of those other IoT device interoperability proposals.
- *Definition of queries in Federated Process Mining.* Healthcare professionals must know how to model as a business process fragment the behavior that defines the user group of interest for a given clinical condition in the Federated Process Mining proposals [6, 89, 7, 88]. While this may be straightforward when the behavior being sought is related to interactions with IoT devices or ADL activities, in other use cases it may not be as straightforward to model such behavior as a process.
- *Adaptation of data integration to different health data standards.* The implemented Personal Health Trajectory allows the integration of distributed health data [8, 91, 9]. However, it remains to be studied to which health data standards such as integration could be applied without breaking the rules to which they are subject. If the Personal Health

Trajectory is not adapted to these standards, its use will not be accepted by certain healthcare institutions.

- *Adaptation of data integration to different data models.* The Personal Health Trajectory offered is ready to integrate data regardless of the technological support and format on which they are stored (as long as they are referencable from the blockchain in some way) [8, 91]. However, the data is integrated into the Personal Health Trajectory without adapting its various data models that a health record may present. This complicates the automatic analysis of the data if mechanisms are not implemented to interpret the data from the different health institutions and devices, in order to extract the relevant information in a common format, and facilitate their analysis.

- *Machine Learning in quantum computing.* With the proposals developed in quantum services, it is possible to use quantum computing in data analysis within classical computing environments. However, there are still not many proposals of Machine Learning and Deep Learning algorithms and technologies ready to be executed in quantum computing. Despite this, their use is beginning to be studied by other researchers [119, 120], so it is a matter of time before this type of algorithms and technologies arrive, solving this limitation.

8.3 Conclusions

In this dissertation, the concept of Personal Health Trajectory has been presented as a way to achieve the transition from the current institution-centered health systems towards new patient-centered health systems by means of software engineering. For this purpose, this dissertation has been supported by the use of several technologies, each of them employed in a novel way in order to solve the limitations presented by their conventional use to solve the problem of patient-centered health systems. An example of this is the use of blockchain technology through the concept of blockchains' federation. With this, integration of distributed health data is achieved that does not present the limitations that are self-imposed by other solutions that use classic blockchain architectures to perform the same integration. In addition to this technology, novel technologies such as Feature Selection, Data Mining, and Process Mining have been used. All of them as part of architectures that break with the use that is usually attributed to these technologies, but that manage to enrich and provide higher quality to the Personal Health Trajectory than the mere integration of data through blockchain.

In addition, procedures and APIs have also been defined that make it possible to offer this Personal Health Trajectory as a framework with which software developers can consume patient health trajectory data. This not only makes it possible to offer this trajectory as isolated information to health professionals in healthcare institutions but also to develop healthcare software applications and systems that consume data from the Personal Health Trajectory.

As a result of all this, we can say that all the proposals developed in this dissertation fit together, work as a whole, and offer a complete, useful, and functional Personal Health Trajectory.

8.4 Future Work

Although a complete, useful and functional Personal Health Trajectory has been achieved throughout the dissertation, there is still work in the general line of the dissertation that can be lines of work for future Ph.D. students. Some of it is drawn from the limitations presented in Section 8.2, while other work is drawn from the state of the research line of this dissertation at the time of writing:

- *Data model standardization.* Although the current Personal Health Trajectory is independent of the format and technological support in which the integrated health records are stored, it must be capable of analyzing their content and extracting the relevant information. Regardless of the data model used to represent the information. This will open the door to being able to analyze data automatically, even if they come from institutions that use different formats to represent the information. As result, a homogeneous Personal Health Trajectory will be achieved, as well as a more useful and functional one.

- *Implementation of the Personal Health Trajectory in different health standards.* If the Personal Health Trajectory proposal offered in this dissertation is going to be applied to the creation of new patient-centered health systems, it is necessary that this proposal complies with the different health standards currently used by health institutions. If the data management procedures and security levels, among others, used by the Personal Health Trajectory do not meet the standards of the institutions, this proposal will never be adopted by them. Furthermore, it is necessary to study the different existing standards and seek to adapt the Personal Health Trajectory to as many of them as possible, so that data from a greater number of institutions can be integrated. This could lead to a completely new line of research resulting in a new Ph.D.

- *Survey in patient-centered health systems.* From the time this Ph.D. was started until the time of writing this document, a couple of years have gone by. The definition of the objectives that were made at the beginning was guided by the software proposals for the creation of patient-centered health systems at that time. Taking into account that the interest in this topic has grown in recent years, for various reasons such as the globalization of health and the covid-19 pandemic, new research has probably emerged that reveals new needs for this type of software solutions. It becomes necessary to review and update the requirements in search of a tentative new version of the Personal Health Trajectory, contemplating also these new requirements.

In addition to these future works, it is also pending the publication of those dissertation results that at the time of writing this document has not yet been published. Mainly, the Feature Selection-based Decision Support Systems framework and the continuation of the Personal Health Trajectory Traceability proposal, as well as the latest version of the blockchains' federation architecture for health data integration. The latter proposal is under review in a very relevant journal at the time of writing. Specifically in IEEE Transactions on Services Computing (2021 JCR Q1, IF: 11.019). Feature Selection-based Decision Support Systems proposal is to be submitted to an indexed journal of medical informatics. The Personal Health Trajectory Traceability proposal is going to be submitted to an international conference, in order to obtain feedback that allows us to publish a more complete and validated version in an indexed journal.

Part IV

Appendices

Appendix A

Voice Assistant to Remind Pharmacologic Treatment in Elders

Authors: *Manuel Jesús-Azabal, Javier Rojo, Enrique Moguel, Daniel Flores-Martin, Javier Berrocal, José García-Alonso, Juan M Murillo.*

Publication type: *International workshop paper.*

Workshop: *Second International Workshop on Gerontechnology.*

Year of publication: *2020.*

DOI: *10.1007/978-3-030-41494-8_12*

Voice Assistant to Remind Pharmacologic Treatment in Elders

Manuel Jesús-Azabal(✉), Javier Rojo, Enrique Moguel, Daniel Flores-Martin, Javier Berrocal, José García-Alonso, and Juan M. Murillo

Quercus Software Engineering Group, University of Extremadura, Cáceres, Spain
{manuel,javirojo,enrique,dfloresm,jberolm,jgaralo,juanmamu}@unex.es

Abstract. Nowadays, the European population is dealing with a serious ageing increment. It is estimated that almost half the population will be over 65 in the next decades, involving society into a vital challenge. This context is specially impacting on the healthcare industry which is facing a significant increase in service and medicine petitions. Elders daily cope with multiple medicine doses, a complex scenario due to the difficult management of drugs and affected by other factors such as solitude or neglect. In this paper a solution is introduced: a voice assistant that reminds the daily pharmacologic dosage using an autonomous system that operates without internet connection.

Keywords: Elder healthcare · Medicine disposal · Ambient assisted living · Voice assistant

1 Introduction

The ageing of European population is an existing fact. Only in Spain, the current percentage of people who is over 65 involve a 20% of the total population, becoming more than 50% in the next decades [1]. Rural areas are the most affected by these circumstances where more than 30% of the population are already senior and aspects like solitude get intensified [2]. The increment of third age individuals implies several challenges to society, specially for the healthcare industry. During the last years, health services and medicine requirements have experienced a severe increase [3]. Almost 50% of health resources expenditure have been intended to third age people eliciting a 30% of all medicine doses and a 75% of chronic treatments.

Elders have the defiance of managing medicine takes, meeting a conflicting scenario due to difficult administration of medication. Around a 15% of elderly population are polimedicated patients [4]. It means that there is a big percentage of third age people who takes five or more medicines for a period of six months or more. This problematic context is specially favoured by the absence of assistance and the age-related cognitive issues. Statistically, this background has an strong impact in society: around 5% of emergencies related to elderly are due to bad medicine management and almost a half of chronic patients at third age does not

J. García-Alonso and C. Fonseca (Eds.): IWoG 2019, CCIS 1185, pp. 123–133, 2020.
https://doi.org/10.1007/978-3-030-41494-8_12

follow properly prescriptions. This set of conducive circumstances are favourable to the use of technology.

Recent technological advances have been specially influenced by new interaction ways. Voice assistants have been one of the most disruptive tendencies at human-computer interaction [5] and has teared down many constraining barriers. Taking advantage of this new paradigm, elders can easily engage with devices which could help them in day-to-day situations.

Taking this into account, voice assistants can be a very suitable technology to remind the elders their daily medicine doses. However, there are some important restrictions derived from the own context that limit possible options. In this paper a possible solution is explained as well the main factors that have been taken into account in the implementation of the project: a voice assistant that helps elders at rural areas reminding the daily medicine takes and clinical appointments. In the following chapters, the platform performance is expose as well as the future possibilities.

2 Overview

The idea of this research project involves a set of challenges that implicate environmental and human factors. There are some important restrictions derived from the own context that limit possible options at development: (1) voice assistant at rural areas and (2) appropriate speech with elders.

1. **Voice assistant at rural areas.** Population in rural areas is generally the most aged [2]. This fact induces that the main targets are those elders who live at rural areas where, widely, homes do not count with an Internet connection. This limitation discards the use of the most popular voice assistant devices such as Alexa from Amazon or Google Home since they require a constant Cloud connection [5].
2. **Appropriate speech with elders.** Since the target users are elders, it is necessary to take into account this fact at speech composition, specially when it references medicines and doses. Usually, third age people do not identify medications through the name or trademark. Physical descriptions or even personal specifications [6] such as position inside a storage rack, are more common. This way, the voice assistant has to allow high customizable options.

On the basis of these two main limitations, the project has been implemented over Snips [7], an open source voice assistant which operates autonomously without Internet connection. Thus, the device has been adapted and integrated into a platform that helps elderly to remind medicine doses and takes. Through this system, medical personnel are able to configure the voice assistant and add prescriptions and appointments (Fig. 1).

The platform follows a simple working scheme that tries to diminish configuration processes and user intervention. *The data synchronisation is the most relevant process. It is based on three main steps: (1) Elderly information* *configuration, (2) Snips synchronisation and (3) Snips operation. This procedure has to be done every time a change is made in the prescriptions or appointments (step 1).*

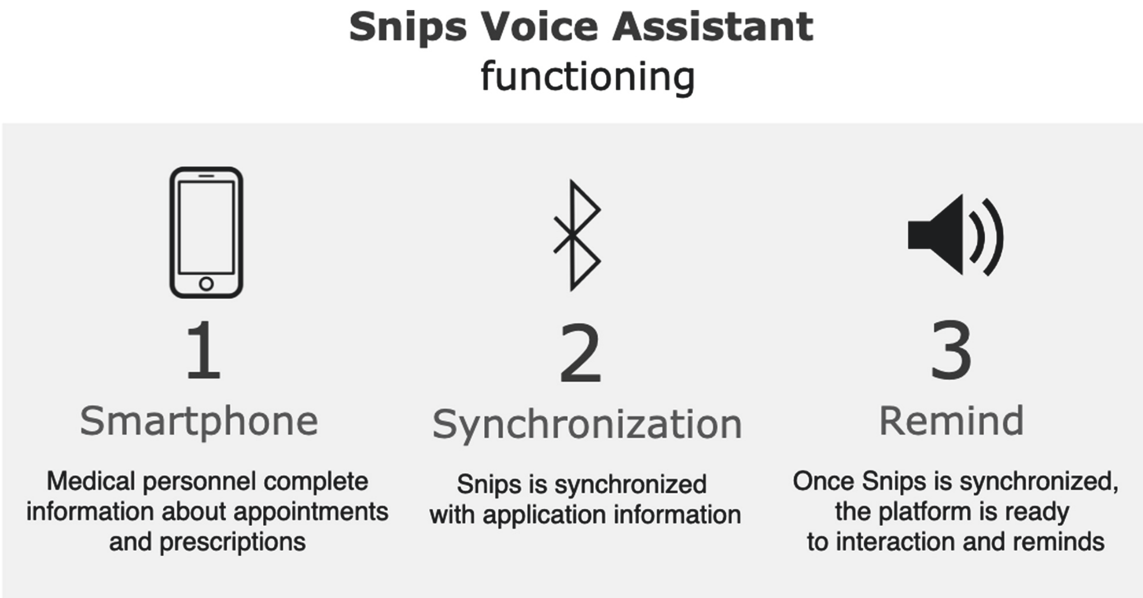


Fig. 1. System overview.

(1) Elderly information configuration. The first step is to specify the elderly information in the smartphone application. Since prescriptions and appointments are clinical data, the medical personnel are in charge of completing this information. Initially, personal data is provided in order to create a new patient profile, once this task is completed, prescriptions and medical appointment can be made. These specs implicate several details:

Prescription. Prescriptions are one key piece in the application and in the full system. This concept associates the elderly with the medication prescribed by the doctor. This way, a medicine can be specified as well as the doses. Since drugs can be consumed at several takes, days of the week and hours are selected, stating the set of reminders that will be lately announced. It is quite important to take into account that the project targets are older adults, therefore, the way medicines are identified has to be taken into consideration. It is usual third age people identify medication following a physical description or even a more personal denomination. This way, the application provides the option of specifying a custom overview to solve this matter.

Appointment. Clinical appointments are really common on elders routine. The variety of motives, places, dates and hours at appointments can turn out to be confusing to elders. In order to solve this, the application integrates a personal user calendar that allow appointments specification. Thus, it includes the involved medical specialist, the place where the meeting will be and the full date.

Once the full information is provided, the application is ready to synchronise with the Snips device.

(2) Snips synchronisation. In contrast to most popular voice assistants, Snips platform is designed to operate in an autonomous way. This means that internet connection is optional, being capable of performing interactions without any Cloud processing. On this basis, an Snips Skill has been develop in order to program schedule reminders using the information from the application. Once all data has been provided in the app, the synchronisation is simply made by Bluetooth, selecting the Snips device as destination. The full step is invisible to user and does not demand any effort. Once this quick step is made, the device is ready to announce the elder's appointments and medical prescriptions.

(3) Snips operation. As a result of the previous tasks, Snips is able to work autonomously and remind elderly about the appointments and medicine takes. This way, the device will announce the medicine that should be taken followed by the custom description at the corresponding daytime. Also, within few days before, medical appointments will be reminded.

The system functioning is really easy and involve just three simple steps. Each component of the platform works independently and they are implemented involving several technologies. In the next chapter, technical architecture details are drawn.

3 Architecture

The platform has been developed into several components that conform the full system. Each element evolves a concrete function to the architecture and can be clearly differentiated through the defined working steps: (1) Smartphone application used to fulfil elderly information and (2) the skill developed over Snips platform.

(1) Smartphone Application. As an starting point, the platform needs information input and requires a way of synchronising Snips devices with that information. Taking into account that one of the premises is the absence of Internet connection at Snips devices, the most suitable idea is using an smartphone application. Thus, data can be easily kept and managed while the physical independence of the phone allows carrying this information into voice assistants installed at elders home.

The smartphone application has been developed using Kotlin. This programming language has motivated the agile development of the platform and has allowed the multiple management of the resources at phone. Through a tab-based navigation model, a fluid browsing has been reached, enabling an easy use and interaction of patient, appointment and prescription information (Fig. 3). Once the application keeps all valid information, synchronisation process is made via Bluetooth (Fig. 2).

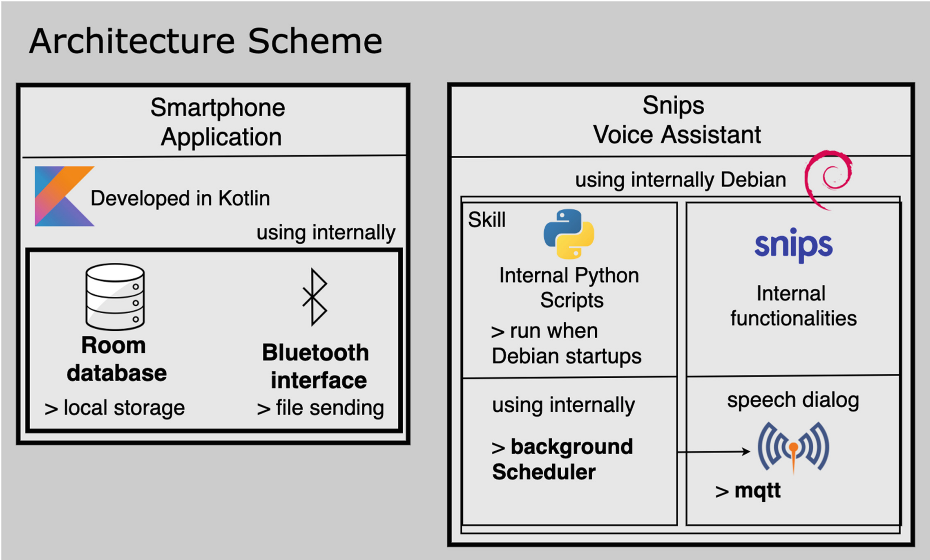


Fig. 2. Voice assistant architecture.

2) Snips skill. Snips device is a voice assistant which main feature is the autonomous working and the independence from Internet connection. This platform integrates a NLP (Natural Language Processor) component that allows the programmer identifying key words and sentences in order to perform tasks. *When the key words are recognised, the instructions to execute are specified using Python language. Internally, Background Scheduler library is used to program reminds. Then, Snips internal functionalities are invoked in order to allow the device to speak.*

Another relevant factor is the capability of integrating functions that commercial platforms disable such as proactivity or device internal settings modification.

Once the full patient information is completed in the smartphone application, Snips can be synchronised. In order to perform this communication, the system follows a quick dialog process: firstly, the application creates a JSON format file (Fig. 4) with the full information of the patient, then, this archive is sent by Bluetooth to Snips and, at last, the device reads this data and programs reminders. Next, this process is explained detailed.

1. **File generation.** When the sync option is selected in the application, it generates a file with the full information of the patient, including appointments and medicine prescriptions. The content is specified in JSON format, enabling an easy interpretation of data.
2. **Bluetooth sending.** Once the application generates the file, it is sent via Bluetooth to Snips.

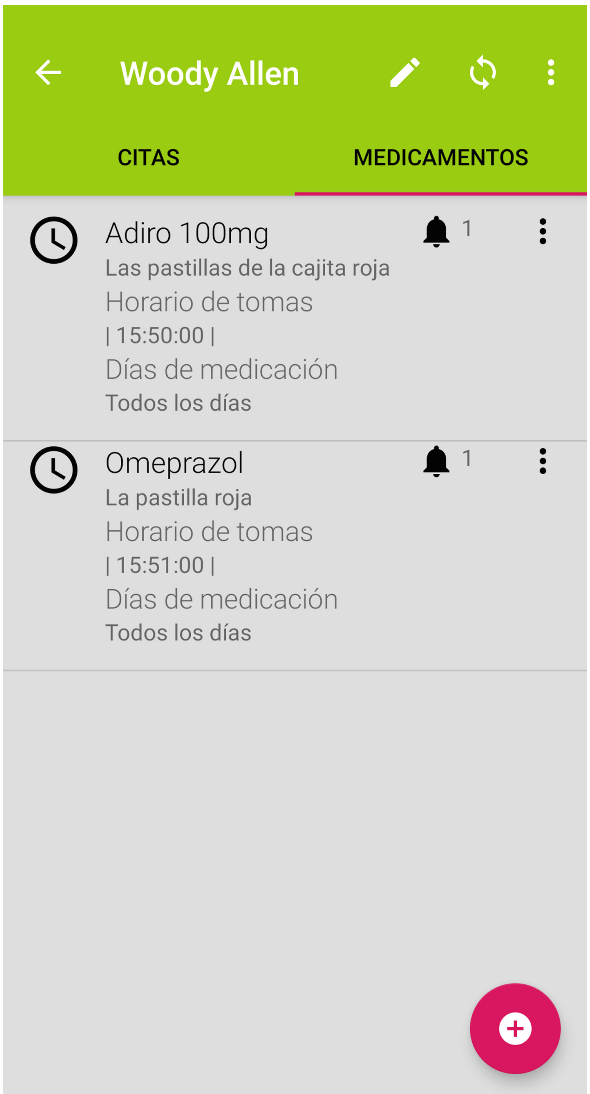


Fig. 3. Application screenshot.

3. **Snips processing.** When Snips receives the file, it identifies the content and new appointments and prescriptions. This way, once information is interpreted, the device launches the reminders and speeches coordinators. As a result of this last step, Snips will remind elderly the medicine doses and takes while announces clinical appointments.

As a result of the development process, Snips is able to recognise the detailed information about prescriptions and appointments. When the corresponding taking hour is reached, the device will announce the medicine name joined the custom description. Furthermore, clinical appointments are notified few days before they take place. All this functions conform the current working of the platform, opening a work line full of possibilities and options to the voice assistant and assuming a very significant improve in elders' life.

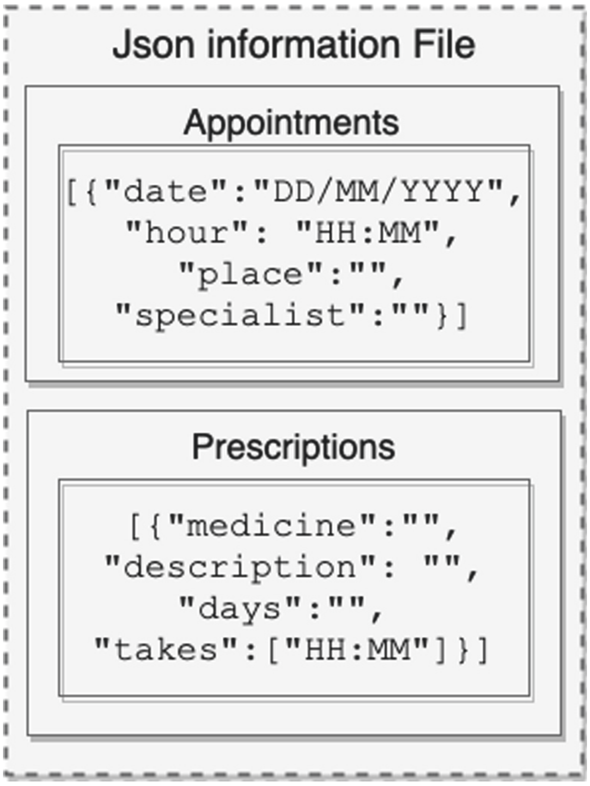


Fig. 4. Json file format.

4 Related Work

Technology is a discipline closely linked with health. The possibilities and advances at digital healthcare are quite relevant and they are becoming a very significant branch in research. Elders are the target users of many projects and the literature offers many ideas to improve their day-to-day activities. In this Section, several projects related to medicine prescriptions reminders are collected, exploring the working and studying the possible impact. This way, related articles are classified into two main clusters: (1) medicine takes reminders and (2) elderly healthcare assistants. This two working groups explore the two main lines of this project.

(1) Medicine takes reminders. Several projects and patents about medicine takes reminders can be found in the literature. The main objective is helping elderly or dementia patients at daily drugs ingestion. Thus, some of the most relevant works are: Medicine Reminder and Monitoring System for Secure Health Using IoT [8], Feasibility study of a robotic medication assistant for the elderly [9] and Multimodal and adaptable medication assistant for the elderly: A prototype for interaction and usability in smartphones [10].

Medicine Reminder and Monitoring System for Secure Health Using IoT [8] specifies the working and architecture pattern that medicine reminders implement. In order to identify the functioning core of these ideas, the article assembles

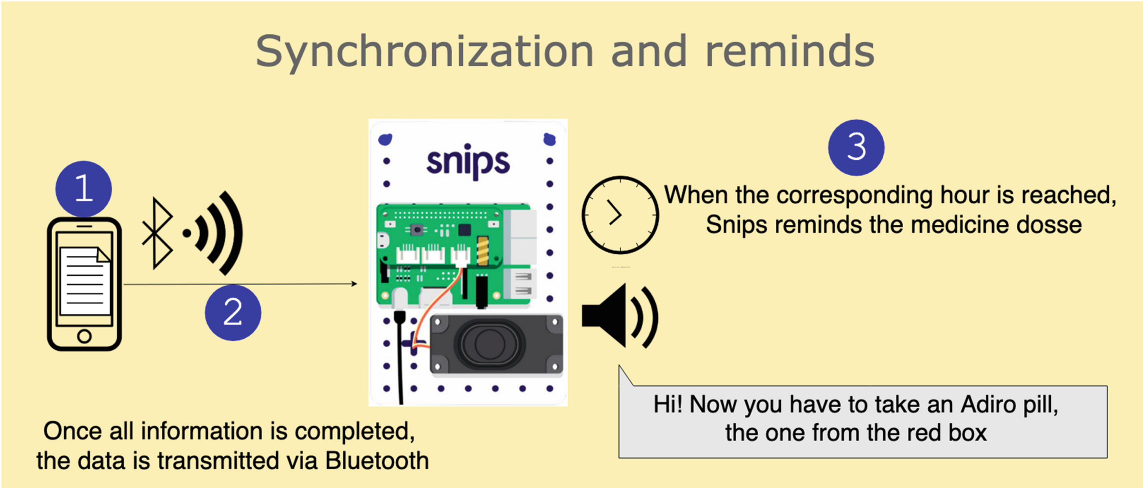


Fig. 5. Synchronization process.

several projects and previous work, drawing a performance schema and analysing the useful use of IoT devices (Fig. 5).

Feasibility study of a robotic medication assistant for the elderly [9] brings the mixed concept of robotic assistant and medication reminders. This way, using a robot equipped with a touchscreen, the device reminds the elderly the drugs that should take, checking if the doses has been taken.

Multimodal and adaptable medication assistant for the elderly: A prototype for interaction and usability in smartphones [10] proposes a solution based on mobile devices that reminds elderly the daily medication. One of the main strengths of the platform is the capability of adaptation to the context, adjusting information output to the user's situation: distance from user's face and screen is calculated thus, icons and fonts are scaled while ambient noise is checked in order to establish a right notifications volume level in each case.

(2) Elderly healthcare assistants. The developed skill in Snips platform opens up a full future work line where options like deep speech responses and proactive care of the elderly can be finely integrated. This way, elderly assistants can be a very powerful tool in order to provide wellness to the user. Literature offers several relevant ideas that match with this premise: iCare: A Mobile Health Monitoring System for the Elderly [11], Pearl: A Mobile Robotic Assistant for the Elderly [12] and Tele-medicine system based on a personal robotic assistant [13].

iCare: A Mobile Health Monitoring System for the Elderly [11] is a healthcare platform based on smartphone and wearable that monitors elderly vitals. Moreover, the system can identify possible emergencies and provides multiple information about the user, allowing relatives, friends and health personnel know about the progression. Furthermore, iCare also includes functions about reminders and medical guidance.

Pearl: A Mobile Robotic Assistant for the Elderly [12] is a platform based on a robot that helps elders at day-to-day tasks. The device works as a personal assistant with two main functions: reminding elderly about tasks like taking medicines or drinking; and guiding people through environments. The robot is based on a well-defined action scheme which includes the possible programmed actions like informing, moving or reminding.

Tele-medicine system based on a personal robotic assistant [13] introduces an elderly tele-assistance system implemented on a robot assistant. In this manner, the system is able to communicate and interact with the elderly on a natural and intuitive way. One of the main functions of the project is remote telemedicine which is mainly based on a video-conference system that allows medical personnel to keep a visual and telematic diagnosis.

All this works are perfect examples of the encouraging work line this project follows. The possibilities new advances provide to the research bring the opportunity of improving notably the elder's life through technology.

5 Conclusions and Future Works

Many older adults daily face with multiple medicine doses. The difficult of managing several medicine brands with various doses and different takes becomes a hard situation for ageing people. Technology can be a suitable option to improve this daily routine, specially voice assistant devices. The purpose this paper describes has the main objective of reminding elderly of the daily medicine takes and the clinical appointments. This way, a voice assistant is a matching solution to the polymedical problem at third age, working successfully at helping in medicine management. *Nevertheless, not all voice assistant platforms adapt to the context of the problem. Popular devices such as Alexa or Google Home require a constant Cloud connection. Therefore, deployment is not possible in areas where there is not Internet connection. Moreover, these voice assistants provide a very restricted development environment. Thus, the Skills operations are limited and functions like proactivity are not possible. On the other hand, Snips Platform is a voice assistant that operates without Internet connection. The working of the device allows the developer to operate with internal options of the voice assistant. This way, it is the best option to the purpose.* The custom capability of the platform assures that user understands the device indications, improving elderly-machine interaction. Since Snips Platform is used to define the assistant, deployments are immediate in every context. The Internet independence enables the use of the device in rural and isolated areas, assuming one of the most disruptive concepts of the project.

The voice assistant has been tested in several lab contexts. During these tests, researchers and students have been using the platform in order to detect possible functional errors. It is quite relevant to guarantee a successful working in the prototype before next versions since it is planned to involve real users in next tests. Moreover, results have been favourable. The voice assistant device has successfully stored and reminded all prescriptions and appointments. Thus, next versions will be tested with final users in a real context.

The implementation of the prototype adjusts elder's need and allow interaction based on natural language and without any learning curve. However, this is the first step in a very relevant work line thanks to the possibilities of autonomous connection and programming faculties. There are pendent interesting tasks that will notably increase platform possibilities like a deep speech implementation or proactive care of the elderly. Next, some of this ideas will be detailed.

A deep speech implementation will be specially useful at user-device interaction. The potential of these functions translates the usage into a better experience that improves medicine management, allowing consults about prescriptions details. *Therefore, the elderly will be able to interact with the voice assistant, asking about the next medicine takes or precising details about future appointments. It will be a substantial feature since it provides an easy interaction between the user and the system. This communication will play a key role in future developments since it can be extended in order to provide fluid speeches with the elderly. This way, the conception of the voice assistant will change into a companion device.*

Proactive care is also a keystone on the future work line. The opportunity of using context information and elderly health reports brings the option of proactive care. This way, the system asks the user about his wellness and medicine effects, giving advices about prescriptions, health and physical care. *It is also a key part at healthcare. The voice assistant device will be able to ask the elderly about issues related to medication. Moreover, a deep study of prescription symptoms can be developed. Since the elderly will answer about doses effects, the voice assistant device will store the reply. When the next synchronisation process is made, the device will provide the information to the medical personnel. This feedback can be essential to successfully adjust the dosage.*

System interconnection is a technical challenge that improves system effectiveness. The possibility of connecting the assistant into several wearables and devices assure medicine notifications will be received. Appliances like vibrating bands and smartphones are examples of devices that would notably increment the platform presence.

This paper brings an idea that notably improves elder's day-to-day. The project is a solid approach to solve polymedical derived problems and provides an easy reference to drugs management and recognition. Future works are evidences of the disrupting ideas the system brings.

Acknowledgment. This work has been partially funded by the 4IE Project (0045-4IE-4-P) and 4IE+ project (0499-4IE-PLUS-4-E) funded by the Interreg V-A España-Portugal (POCTEP) 2014–2020 program, by the Spanish Ministry of Science, Innovation and Universities (RTI2018-094591-B-I00), by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

1. Bloom, D.E., et al.: Macroeconomic implications of population ageing and selected policy responses. Lancet **385**(9968), 649–657 (2015). https://doi.org/10.1016/S0140-6736(14)61464-1. http://linkinghub.elsevier.com/retrieve/pii/S0140673614614641
2. Rodríguez Rodríguez, P.: Envejecimiento en el mundo rural: necesidades singulares, políticas específicas. Observatorio de Personas Mayores, Madrid. NIPO: 216-04-006-9. http://www.imsersomayores.csic.es/documentos/documentacion/estudiosyresultados/perfiles/boletinsobreenvejec11.pdf. 30 p.
3. McDonough, R., Cooper, J.J.: Drug-related problems in older adults. J. Am. Pharm. Assoc. (Washington, DC: 1996) **42**(5 Suppl 1), S32–3 (2002)
4. Mira, J.J., et al.: Physician patient communication failure facilitates medication errors in older polymedicated patients with multiple comorbidities. Fam. Pract. **30**(1), 56–63 (2012)
5. Hoy, M.B.: Alexa, siri, cortana, and more: an introduction to voice assistants. Med. Ref. Serv. Q. **37**(1), 81–88 (2018)
6. Cardarelli, R., Mann, C., Fulda, K.G., Balyakina, E., Espinoza, A., Lurie, S.: Improving accuracy of medication identification in an older population using a medication bottle color symbol label system. BMC Fam. Pract. **12**(1), 142 (2011)
7. Snips Corp.: Snips. https://snips.ai/
8. Zanjal, S.V., Talmale, G.R.: Medicine reminder and monitoring system for secure health using IOT. Procedia Comput. Sci. **78**, 471–476 (2016)
9. Tiwari, P., et al.: Feasibility study of a robotic medication assistant for the elderly. In: Proceedings of the Twelfth Australasian User Interface Conference-Volume 117, pp. 57–66. Australian Computer Society, Inc. (2011)
10. Ferreira, F., Almeida, N., Rosa, A.F., Oliveira, A., Teixeira, A., Pereira, J.C.: Multimodal and adaptable medication assistant for the elderly: a prototype for interaction and usability in smartphones. In: 2013 8th Iberian Conference on Information Systems and Technologies (CISTI), pp. 1–6. IEEE (2013)
11. Lv, Z., Xia, F., Wu, G., Yao, L., Chen, Z.: iCare: a mobile health monitoring system for the elderly. In: 2010 IEEE/ACM Int'l Conference on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing, pp. 699–705. IEEE (2010)
12. Pollack, M.E., et al.: Pearl: a mobile robotic assistant for the elderly. In: AAAI Workshop on Automation as Eldercare, vol. 2002, pp. 85–91 (2002)
13. Barea, R., Bergasa, L., López, E., Escudero, M., Hernández, J., Willemaers, Y.: Tele-medicine system based on a personal robotic assistant. In: 10th IEEE International Conference on Methods and Models in Automation and Robotics MMAR, vol. 4, pp. 909–915 (2004)

Appendix B

Automating the Interactions among IoT Devices using Neural Networks

Authors: *Javier Rojo, Daniel Flores-Martin, Jose Garcia-Alonso, Juan M Murillo, Javier Berrocal.*

Publication type: *International workshop paper.*

Workshop: *3rd International Workshop on Context-awareness for Multi-device Pervasive and Mobile Computing - Collocated with the IEEE International Conference on Pervasive Computing and Communications (Percom) (2021 GGS Class 1 Core A+).*

Year of publication: *2020.*

DOI: *10.1109/PerComWorkshops48775.2020.9156111*

Automating the Interactions among IoT Devices using Neural Networks

Javier Rojo*, Daniel Flores-Martin*, Jose Garcia-Alonso*, Juan M. Murillo* and Javier Berrocal*
*University of Extremadura
Caceres, Spain
Email:{javirojo, dfloresm, jgaralo, juanmamu, jberolm}@unex.es

***Abstract*—The number of Internet of Things (IoT) devices is growing at an unstoppable pace. In most cases, the proper functioning of these devices requires human intervention. Due to this growth, people will have to configure more and more devices leading to the investment of a considerable effort and time. Nowadays, some works try to automate the user actions with IoT devices by using machine learning algorithms based on the relationships among devices or the previous human behaviour. However, these proposals do not make use of contextual information obtained from the devices themselves or they employ complex sets of prediction models. This paper proposes a neural network-based solution to predict the devices behaviour by using previous interactions and contextual information as input variables. Thanks to this, device interactions can be predicted and automated, even without having previous records, by knowing behaviours of devices of the same type in similar environment.**

***Index Terms*—IoT Device interactions, Context-awareness, machine learning, neural networks.**

I. Introduction

IoT devices make people's lives easier by offering them improvements in their daily routines [1]. This is one of the reasons why these devices have a high penetration in many environments such us *smart homes*, *smart cities* or *smart offices*, for instance. However, although in so many cases these devices simplify people's lives, nowadays, they usually require a direct command from the user each time a person needs to perform an action or to change the defined configuration.

This supposes an effort that increases when the number of devices in the environment raises, to the point that the perceived benefit of applying the IoT paradigm is not the expected one. To manually change a single configuration is not hard but, when the number of devices and the interactions among them increase, the required effort increases overwhelmingly. Based on some predictions [2], in 2025 will be 75 billion IoT devices, which means an average of 9 devices per person, and even more in the developed countries. Therefore, managing these devices and their interactions will require a great effort [3].

In order to reduce this effort, different approaches have been proposed for automating some of these tasks. For instance, by analyzing the relationships between devices [4] [5] or by defining custom operating models for each device [6], but again each time an interaction changes, the models have to be reconfigured. Other works are based on machine learning algorithms that are able to predict and adapt future interactions with the devices based on the previous interactions [7] [8]. Nevertheless, these proposals make use of complex systems that combine different techniques and employ each one depending on the environment and the number of the devices, reducing the responsiveness and increasing the computational load.

Therefore, in this paper we propose a neural network-based solution for predicting the interactions among IoT devices that can be used in almost any environment. To that end, it makes use of contextual information provided by the devices themselves such as its kind, how they interact, the status of the environment, etc. From this information, the neural network is able to predict actions and the interaction among devices when the contextual information changes (users, time, devices, specific values, etc.).

One of the advantages of this solution is that the predictions can be made with a small amount of information and, every day, the model can be refitted with new records. Thanks to this, the system can re-adapt the predictions to the changes and user's needs. The solution has been tested with semi-synthetic data and in a real environment for three weeks obtaining a probability of success of 85.34%, highly reducing the effort required to interact and reconfigure these devices when the user's needs change.

The rest of the document is structured as follows. Section II shows the motivations of this work and some related works. Then, Section III describes the proposed neural network-based solution. Section IV details the validation performed to evaluate the proposed solution. Finally, in Section V the conclusions of this work are exposed.

II. Motivations and Related Works

IoT devices allow users to automate their daily tasks. There are IoT devices for a wide range of tasks. However, when the number of IoT devices with which the user must interact grows a lot, the number of actions and configurations to be performed also grows, being difficult to manage all these devices. To better understand this problem, an example is proposed below:

Suppose an user named Peter, who is an enthusiastic of technology and interacts with IoT devices in their common environments. Every time Peter arrives home, he turns on the light and the television in the kitchen. Peter feels the need for these devices to recognize that he arrived home and automatically do these tasks for him. He tried to program their actions at a certain time, but since his work schedule *is flexible, he does not always arrive home at the same time, which means that the devices are turned on before or after the appropriate time. After dinner, he usually goes to his living room, where he has a bulb with a dim light and turns on the television to watch his favourite program. However, during the last few weeks he is starting to read, so that every day he has to manually turn the television off and increase the luminosity (or change the configuration). These manual interactions make Peter to start thinking that the deployment of these intelligent devices does not provide any advantage.*

As shown above, there is a need for approaches learning from the user behaviour and from the contextual information in order to automate these actions without the need for the user to configure and reconfigure them whenever her/his needs change. Thus, the user can focus on performing actions that are not usual or do not follow a pattern of behaviour over time. This would reduce the number of actions done by the user, something important in environments with a growing number of IoT devices [2]. Therefore, technological alternatives for predicting future actions of the user, based on their previously registered behaviour and the contextual information, should be developed.

During the last few years, for the device interactions prediction, different techniques and methodologies have been proposed. This is an important topic in researches linked with IoT, especially in Ambient Assisted Living (AAL) [9], a paradigm oriented to improve people quality of life using Information and Communication Technologies (ICT). In this sense, Machado et al. [4] propose a solution using ontologies for establishing relationships between devices of the same environment. Ciocarlie et al. [5] also propose a solution for predicting behaviours using action links between devices in the same environment. In addition, Paternò et al. [6] propose the definition of customizable rules that can be used in trigger-action programming paradigms. These rules can be customized by any user and they will be triggered by a machine learning system to recommend future rules for the device. Other proposals are focused on the prediction of device interactions by using *context-awareness* information instead of the relationship between devices. Alhafidh et al. [7] [8] propose some comparisons about different machine learning classification models, by using them in an isolated way or assembling them. However, chaining different models require for these proposals to find a balance between the system responsiveness and the accuracy of prediction. Both dimensions are crucial for IoT applications [10].

The work presented in this paper is focused on the use of contextual information to predict the interactions that will be performed among IoT devices; using a single model. Besides, the proposed solution has been evaluated in five real scenarios obtaining very good accuracy in all of them.

III. PREDICTING THE INTERACTIONS

The proposed solution is divided into four sections: a) first, the synthetic data were generated to evaluate the technological alternatives to make the predictions; b) then, each alternative was evaluated with the generated data in order to know which one provides the best results in a simulated environment; c) next, the best technique was selected and adapted in order to get the best predictions regarding the responsiveness and the accuracy; and d) finally, the developed prototype was evaluated in five real scenarios.

A. Generation of the synthetic data

To measure the available algorithms and techniques, it is required a dataset to train the models and evaluate them. Currently, in the moment of developing this work, there is no available dataset with the contextual characteristics that this proposal requires for automating the IoT interactions (users present, type of devices, connection type, environment status, etc.). So that, it is necessary to generate our own data. Generating synthetic data is the quickest method to start collecting data that serve us to identify the technique or the set of techniques more appropriate to solve our problem [11].

Synthetic data was generated to make a first validation in order to choose the best prediction model. These data are generated with TheONE Simulator [12]. Initally, The is aimed to to simulate message routing between nodes with various Delay-tolerant Networking (DTN) routing algorithms and sender and receiver types. Nevertheless, although its objective is different, this tool was chosen because it can simulate different movement patterns, among which are the movement patterns of a person in his day-to-day life through different environments (office, home, car,...). This tool allowed us to simulate the interaction among IoT devices in different environments. In order to generate the synthetic data its *core* library has been modified to make the simulation more realistic.

In the TheONE Simulator, a series of environments were defined (such as the one defined in Section II), in which there were different types of devices that can be used to perform different actions. The action to be performed is selected based on a probability and also is based on the time of day, the context of the environment and the context of the user.

In a first version of the data generation, a relationship between the probabilities of performing each action with a device and the time, was not stipulated –only some contextual information about the environment and the devices were considered– (Fig. 1.a). For instance, the probability of turning on the kitchen oven was the same at mealtime than at 3 in night. This resulted in a poor generation of synthetic data, which had to be modified

to obtain more realistic data. In a second step, the time was considered as another contextual characteristic together with the device information and the contextual data (Fig. 1.b).

In the data collection, certain data from the environment have been collected (*context-awareness* information), such as the day of the week, the time at which the action is performed (rounding to the nearest o'clock time) and a timestamp (which are not used still in the selected model); and device data, such as its identifier and its device type. Also, the performed actions were always recorded. In total, we simulated 163.039

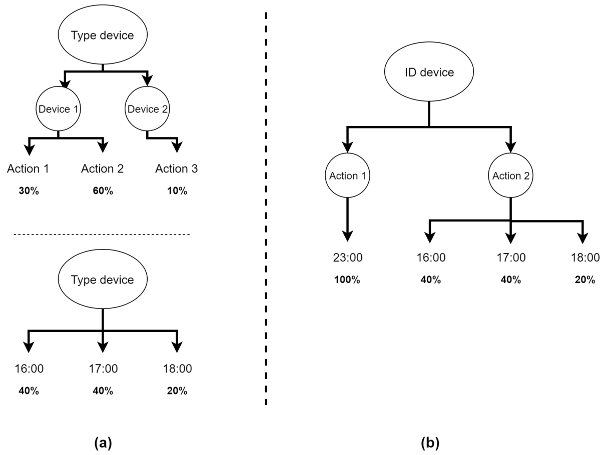


Fig. 1: Synthetic data generation: (a) Without relating actions and hours; (b) Relating actions and hours.

interactions among IoT devices, in four different environments, with a total of 14 devices. We simulated the interactions of an user in his/her everyday environments with devices such as smart bulbs, speakers or plugs, for example.

B. Machine Learning algorithms

Different machine learning techniques have been analyzed to predict and automate the device interactions, based on contextual data and previous human behaviours with the same devices or devices of the same type.

Before analyzing the different machine learning models, it is necessary to understand the data pre-processing. Thanks to this, better performance in predictions can be obtained. In this process, all fields were serialized, based on their different values, in binary fields.

Once the data were pre-processed, different techniques were evaluated to identify their accuracy and responsiveness. To increase the responsiveness and reduce computation load, we are focused on using a single model. The evaluated models and their results can be seen in Table I. Please, note that these results are with synthetic data. Once they are applied in real scenarios, the accuracy can be slightly lower since some actions can be executed without following a predefined pattern.

TABLE I: Table of accuracy per model.

ML Model	Accuracy	Delay (s)
Logistic Regression	0.5329949	10.92
SVM	0.9999182	∞(>600)
Decision Tree	0.6666667	0.0019
Random Forest (80)	0.9999386	22.58
KNN (n=17)	0.9999182	247.60
Neural Network	0.9996013	163.73

As can be seen in Table I, Random Forest, KNN and Neural Networks provide promising results. For KNN, we evaluated the optimal number of neighbours (from K=1 to K=30) in terms of accuracy, obtaining K=17. However, the algorithm was quite slow (it took 30 minutes to find the optimal number of neighbours and be trained with the synthetic dataset), without offering so much superior accuracy to other alternatives studied. Therefore, it was discarded.

Because of the performance and the short time needed to train the model and make predictions, we decided to use neural networks. Random Forest also offers good times, however, in other tests performed, where the number of devices increased and the relationships were more complex, its accuracy decreased with respect to the neural network. The definition of this neural network will be explained in section III-C. Combined models will not be used, as proposed by other solutions, because the performance obtained with this single model is good enough and it reduces the computational load.

C. Neural Network for predicting interactions

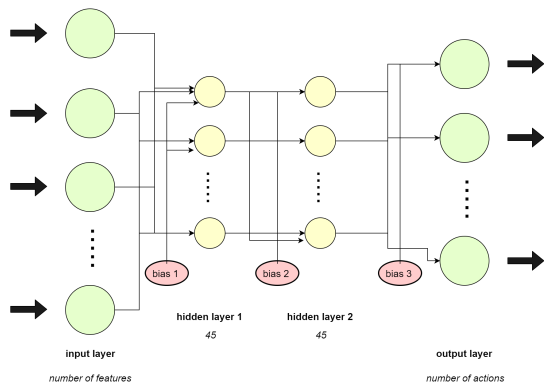


Fig. 2: Neural network definition.

The neural network (Fig. 2) has as many input neurons as characteristics our data have (after obtaining their *dummies* or serializing the attributes to binary fields). The number of outputs offered by the network was equal to the number of different actions that exist in the devices. When new devices are added, the number of outputs also change, and the network is redefined. The network gives as output the probability that each action is the action to be performed, after applying the *softmax* function, that convert output values to probability values (softmax output sum of values must be 1, that indicates that the probability of every outputs is 100%). A *argmax* function is applied to that output to obtain the most probable action. To the rest of the layers, a *sigmoid* function as activation function is applied. The *sigmoid* functions are more specifically defined as a squashing function. Squashing functions limit the output to a range between 0 and 1, making these functions useful in the prediction of probabilities. All these functions are used, therefore, to be able to predict the action or the interaction that should be executed among IoT devices.

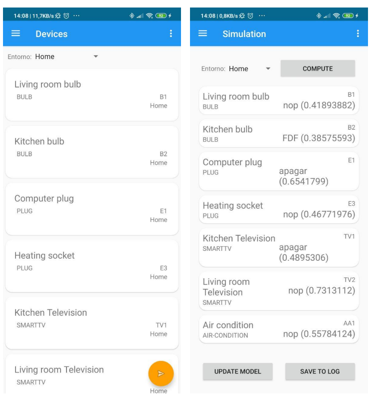
The number of hidden layers and the number of neurons for these layers were decided after testing different combinations, and trying to reduce the probability of *overfitting*. Also, it has been added a *bias* neuron in each layer, to reduce the bias of data. This was determined by using the synthetic dataset generated.

To train the model, it was decided to divide the data with a *batch_size* of 100, making 3000 epochs. This number of iterations is necessary, as it has been stipulated a very low learning rate (*0.000125*) for the selected learning algorithm (*AdamOptimizer*). This algorithm was used because it is well suited for problems with large quantity of data and it requires little memory resources. A *sparse softmax cross-entropy with logits* was used for training. This is a method employed when the prediction is based on a classification problem with probabilities. The value of the coefficient has been set based on the graph of the loss coefficient generated with the loss value of each epoch [13].

To do the implementation of this neural network the technology used was *TensorFlow*. This is due to the generated models are compatible with their execution in mobile devices with *TersorFlow Lite* [14].

D. Prototype

A prototype has been developed that allows us to validate the predictions performed by the selected model to automate the device interactions. In this sense, a client-server architecture has been chosen for the prototype, consisting of an Android client and a Python server. A server in the *cloud* is used to define and train the model. The trained model is downloaded by the Android application to be able to predict the interaction of that device with the rest of IoT devices in the environment. This allows us to predict and automate the interaction of the owner of the mobile device.



(a) (b)

Fig. 3: App views: (a) IoT devices of each environment; (b) Simulation of device interactions predictions.

In this sense, a specific model is created for each user/mobile device. The generated model is linked to the user using her/his *Google Advertising ID*.

The developed application can execute the defined model and simulate the interactions with IoT devices. Currently, it can simulate different environments with different not-real IoT devices (Fig. 3a). With these devices, the different actions can be performed manually and saved in a registry. This registry is used for refitting the model every day. Then, the model is used to automate the interactions with the devices. If an interaction is incorrectly predicted, the user can correct it (Fig. 3b). This information is used to provide feedback to the model in order to improve future predictions. All the information generated by the application is stored in a log (such as the *context* of the prediction, the predicted action, if the action was corrected, the correct action, etc.). That log was used to evaluate the performance of the selected techniques.

IV. Validation

To validate the system, the developed application has been used by five users in their daily routine. Five different scenarios and IoT devices were defined where each user had to use the application in those devices depending on their usual behaviour.

A. Scenarios definition

Each of the defined scenarios was used to generate metrics separately. On the one hand, three of the five scenarios were used to record information on tasks that are performed when the user arrives at a specific environment (Scenarios 1 to 3). On the other hand, the other two scenarios were used to record all the actions that the user performs when s/he already is in a specific situation (Scenarios 4 and 5). The scenarios are defined as follows:

- **Scenario 1:** A scenario that represents the behavior of a person who works from Monday to Friday morning. In the afternoon, s/he is usually at home watching TV.
- **Scenario 2:** A scenario that represents the behavior of a person who works from Monday to Friday (morning and afternoon). On Saturday s/he is at home and on Sunday s/he goes to her/his parents' home.
- **Scenario 3:** A scenario that represents the behavior of a person who works from Monday to Friday morning. In the afternoon, s/he does not follow a pattern of behavior.
- **Scenario 4:** A scenario that represents the behavior of a person who works from Monday to Friday, morning and afternoon (except Fridays). On weekends s/he goes to her/his parents' home.
- **Scenario 5:** A scenario that represents the behavior of a person who works from Monday to Friday morning. In the afternoon, s/he goes to her/his parents' home by car.

The validation lasted three weeks. The two first weeks were used for training the model with information about the different actions that the users performed with the present devices in each environment. And the last week was used for the testing phase in order to get prediction and evaluate them. Some predictions were also made during the two weeks of training, to check how much data were needed for the system to start learning new behaviours and how the predictions improved with new records. However, this depended a lot on how frequent the behaviour is.

B. Results

First, regarding the responsiveness, it is interesting to indicate that on average **11.05 seconds** are required to refit the neural network with the inputs of each user every day and **1.35 milliseconds** on average are required to make a prediction. As can be seen, the responsiveness is very good for almost any IoT application. Other similar proposals [8], are getting prediction times of 896.1 milliseconds (when the number of devices is small) and 1.21 seconds (when the number of devices is higher). Training times are not included in these proposals.

Second, regarding the accuracy, the results obtained for each scenario can be seen in Table II. In this table, the number of predictions, the correct and the incorrect ones are detailed. This table also shows the *total* row that represents the joint results for every scenario.

TABLE II: Table of predictions.

Scenario	Predictions	Correct	Failed	Accuracy
Scenario 1	109	83	26	0,76
Scenario 2	245	212	33	0,86
Scenario 3	69	64	5	0,92
Scenario 4	78	67	11	0,85
Scenario 5	72	63	9	0,87
Total	573	489	84	0,85

By analyzing the joint results for every scenario, we have to notice that 84 predictions were not correct. According to this, we detected that 76 were produced by trying to predict actions that do not have a specific behaviour pattern, since there were records of different actions for the same device in the same context, and for the same user. For example, imagine a person who sets a different television channel every day when arriving at home. If the system tries to predict which channel the person will choose, the probability of getting a correct prediction is low. For the other 8 incorrect predictions, the model was not able to learn the action. Therefore, it can be said that only 8 out of the 573 predictions were not correct.

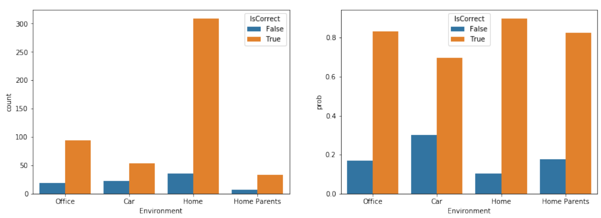


Fig. 4: Probability of predictions per environment.

Besides, if it is assumed that the number of failures is mainly due to actions that cannot be predicted, it can be observed in which environments (Fig. 4) and for what types of devices (Fig. 5) the behaviour is more changing and our model can obtain worse results. As can be seen in Fig. 4 and Fig. 5, the environment with a higher probability of failure is the *"Car"* and the type of device with the most failures

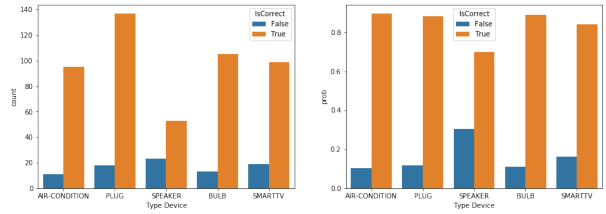


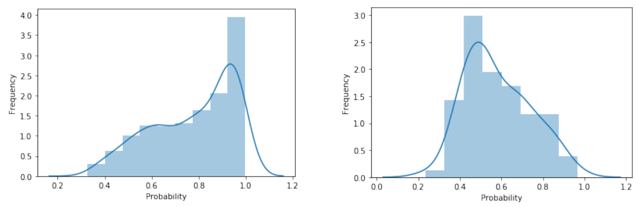
Fig. 5: Probability of predictions per type of device.

is the *"Speaker"*. Evaluating the obtained logs, we identified that this is because the users make short trips by car and the speaker is turned on and off in a short time and because they do not listen to the same type of music on the same route. In these situations, the presented system is more likely to fail.

TABLE III: Table of measures over probabilities.

Measure	Correct predictions	Failed predictions
Min. value	0.3266	0.2347
Max. value	0.9970	0.9667
Average	0.7762	0.5817
Typical Deviation	0.1763	0.1563

In addition, we also evaluated the probability of success for every prediction in order to identify a *threshold* that allows us to know when a predicted action should be performed or not. In Table III can be appreciated the average, the maximum and the minimum value and standard deviation for the probability of the correct and the failed actions.



(a) (b)

Fig. 6: Univariate distribution of probabilities: (a) for correct predictions; (b) for failed predictions.

TABLE IV: Table of measures over threshold.

Threshold	False neg.	False pos.	Correct	% Success
0.40	41	55	477	0.832461
0.42	54	44	475	0.828970
0.44	67	42	464	0.809773
0.46	76	41	456	0.795812
0.48	84	36	453	0.790576
0.50	99	34	440	0.767888

Finally, to determine the *threshold*, an *univariate* distribution has been created with the value of the probability of success of the correct (Fig. 6a) and failed (Fig. 6b) predictions. Thanks to these data, and reducing the number of false positives even if the accuracy is reduced, it can be determined that the best *threshold* is over 0.4 and 0.5. Besides, in Table IV it can be observed that a *threshold* of 0.42 is better, because a lower *threshold* include more false positives.

In conclusion, it can be stated that the algorithm has been able to correctly predict 85% of the interactions, failing only in 1% of the predictions or when the performed actions do not follow a pattern.

V. Discussion and Conclusions

In this paper, a system that allows us to predict interactions with the IoT devices in an environment has been proposed. This approach makes use of contextual information from the environment, previous interactions and the devices' information. To do this, a neural network was used after evaluating the performance in accuracy and prediction time.

These solutions are required in order to be able to implement a true IoT paradigm in which devices are used to automate tasks instead of leading the user to be constantly interacting and re-configuring the different devices depending on people' needs. In addition, the presented system is able to learn and adapt the prediction to the new needs.

We are currently working on integrating the defined model with real and heterogeneous devices. To that end, we are combining the presented model with a framework already defined to improve the interactions among heterogeneous devices by means of semantic web [15]. It is also intended to be able to define and to train the model in the final device, without the need for a server to train the model and send it to the device to make the predictions.

Finally, we are also working on deploying this model in social environments, in which the behaviour is not the same depending on whether a person is accompanied or not, who accompanies them and what are the needs of each one.

For this experiment, the model is executed in the user's mobile device, which will be the only one performing the interactions with the real IoT devices. However, this solution will not work in social environments, where we will need a network of mobile devices that communicate with each other or a master device to which all IoT devices and smartphones are connected.

Resources

- Full validation document [16].
- Dataset of synthetic data [17].
- Datasets of actions performed by each person in validation phase [18].
- Logs of results of predictions in validation phase [19].

Acknowledgment

This work was supported by the project 0499 _4IE_PLUS_4_E funded by the Interreg V-A España-Portugal 2014-2020 program, by the project RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE) FPU17/02251 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

[1] "How Internet of Things (IoT) effects on our daily lifestyle." [Online]. Available: https://www.futurescope.co/internet-of-things-iot/

[2] "• IoT: number of connected devices worldwide 2012-2025 — Statista." [Online]. Available: https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/

[3] D. Flores-Martín, J. Berrocal, J. García-Alonso, C. Canal, and J. M. Murillo, "Enabling the interconnection of smart devices through semantic web techniques," in *Web Engineering - 19th International Conference, ICWE 2019, Daejeon, South Korea, June 11-14, 2019, Proceedings*, ser. Lecture Notes in Computer Science, M. Bakaev, F. Frasincar, and I. Ko, Eds., vol. 11496. Springer, 2019, pp. 534–537.

[4] G. M. Lunardi, F. A. Machot, V. A. Shekhovtsov, V. Maran, G. M. Machado, A. Machado, H. C. Mayr, and J. P. M. de Oliveira, "IoT-based human action prediction and support," *Internet of Things*, vol. 3-4, pp. 52–68, oct 2018.

[5] G. F. Ciocarlie, B. Copos, I. Agadakos, G. Ciocarlie, T. Lepoint, U. Lindqvist, and M. Locasto, "Butterfly Effect: Causality from Chaos in the IoT," Tech. Rep., 2018. [Online]. Available: https://www.researchgate.net/publication/327515023

[6] F. Paternò and S. Alawadi, "Towards Intelligent Personalization of IoT Platforms End User Development; Internet of Things; Trigger-Action Programming ACM Reference format," Tech. Rep., 2019. [Online]. Available: https://www.researchgate.net/publication/331876007

[7] B. M. Alhafidh, A. I. Daood, and W. H. Allen, "Poster abstract: Comparison of classifiers for prediction of human actions in a smart home," in *Proceedings - ACM/IEEE International Conference on Internet of Things Design and Implementation, IoTDI 2018*. Institute of Electrical and Electronics Engineers Inc., may 2018, pp. 287–288.

[8] B. M. Hasan Alhafidh, A. I. Daood, and W. H. Allen, "Prediction of Human Actions in a Smart Home Using Single and Ensemble of Classifiers," in *SoutheastCon 2018*. IEEE, apr 2018, pp. 1–8. [Online]. Available: https://ieeexplore.ieee.org/document/8479270/

[9] "Descripción general - Programa "Active Assisted Living" (AAL) - Portal de Ayudas del Mº de Industria, Comercio y Turismo." [Online]. Available: http://www.mincotur.gob.es/PortalAyudas/programaAAL/Descripcion/Paginas/descripcionPrograma.aspx

[10] P. Bellavista, J. Berrocal, A. Corradi, S. K. Das, L. Foschini, and A. Zanni, "A survey on fog computing for the internet of things," *Pervasive and Mobile Computing*, vol. 52, pp. 71–99, 2019. [Online]. Available: https://doi.org/10.1016/j.pmcj.2018.12.007

[11] "Generación de datos sintéticos: una habilidad imprescindible para los nuevos científicos de datos." [Online]. Available: https://towardsdatascience.com/synthetic-data-generation-a-must-have-skill-for-new-data-scientists-915896c0c1ae

[12] "Information — The ONE." [Online]. Available: https://akeranen.github.io/the-one/

[13] "CS231n Convolutional Neural Networks for Visual Recognition." [Online]. Available: http://cs231n.github.io/neural-networks-3/

[14] "How to Deploy TensorFlow to Android (feat. TensorFlow Lite)." [Online]. Available: https://medium.com/datadriveninvestor/how-to-deploy-tensorflow-to-android-feat-tensorflow-lite-957a903be4d

[15] D. Flores-Martín, J. Berrocal, J. García-Alonso, and J. M. Murillo, "Towards a runtime devices adaptation in a multi-device environment based on people's needs," in *IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2019, Kyoto, Japan, March 11-15, 2019*. IEEE, 2019, pp. 304–309. [Online]. Available: https://doi.org/10.1109/PERCOMW.2019.8730859

[16] J. Rojo, "Full validation document," 2019. [Online]. Available: https://drive.google.com/file/d/1fYYtRZuXTqkeualkG-HVdIpbqj1Koe30/view?usp=sharing

[17] ——, "Dataset of synthetic data," 2019. [Online]. Available: https://drive.google.com/file/d/1WzhHA8G0pkiCI3TqiRuw6FC5MxWNzkVZ/view?usp=sharing

[18] ——, "Datasets of actions performed by each person in validation phase," 2019. [Online]. Available: https://drive.google.com/file/d/1VBzUSrx3Vzl_JTo5XK-Klb9HUHs_FXh7/view?usp=sharing

[19] ——, "Logs of results of predictions in validation phase," 2019. [Online]. Available: https://drive.google.com/file/d/1-WlX8l-H82QqrWlmoGurWXQ0qPLCXGDW/view?usp=sharing

Appendix C

A Personal Health Trajectory API: Addressing Problems in Health Institution-Oriented Systems

Authors: *Javier Rojo, Juan Hernandez, Juan M Murillo.*

Publication type: *Conference paper (PhD Symposium).*

Conference: *International Conference on Web Engineering.*

Year of publication: *2020.*

DOI: *10.1007/978-3-030-50578-3_37*

2021 GGS Class (Rating): *3 (B-).*

A Personal Health Trajectory API: Addressing Problems in Health Institution-Oriented Systems

Javier Rojo(✉), Juan Hernandez, and Juan M. Murillo

University of Extremadura, Cáceres, Spain
{javirojo,juanher,juanmamu}@unex.es

Abstract. Each person interacts with multiple health institution's systems along their life. These systems are usually developed to fulfill the specific needs of sanitary organizations or Web of Medical Things manufacturers. However, most of the times these information systems aren't interconnected, making it very difficult to put in common the information of a patient scattered in various systems. Thus, it's necessary to develop solutions that allow health information systems developers to consult all the information of an user across the multiple health's information systems it is scattered and to offer this information organized as the Personal Health Trajectory of the user (a succession of Personal Health Records ordered by time). This paper proposes a solution for the integration of heterogeneous health information systems, the processing of their data and its provisioning in a health trajectory perspective through an API. Thus, software developers of healthcare solutions can leverage this API to develop a new generation of person-oriented solutions.

Keywords: Personal Health Record · eHealth · Personal Health Trajectory · APIs

1 Introduction

Technological advances in the field of health information systems are making it possible to improve the services provided to patients. Specifically, the use of smart connected devices from the Web of Medical Things (WoMT) [10] in combination with traditional medical data is used to provide advanced solutions.

Nevertheless, most of these solutions work on data from a single information system. In a globalized society, like the present one, a person will surely interact with several health systems along their life. Not to mention the pervasive presence of WoMT devices, which generate data outside these institutions. Each of these systems keeps its data separate, which could mean that crucial information for the person's health could be not available when needed [13]. All these data are useful, but they take on added value when put together.

To better exemplify the problems this entails we present Paula's case. *Paula is a Spanish women who suffers from diabetes. On one of her trips to China,*

M. Bielikova et al. (Eds.): ICWE 2020, LNCS 12128, pp. 519–524, 2020.
https://doi.org/10.1007/978-3-030-50578-3_37

Paula suffers a fainting spell due to hypoglycemia. She is treated in a health center in China, where she is measured for blood glucose. However, when Paula returns to Spain, she cannot give the data of those measurements to her usual doctor, because they have been registered in the Chinese health system. Something similar happens with her smart glucometer. Only a few of the measurements she takes at home are transcribed to her health record. If Paula has another fainting spell, her doctor cannot access Paula's latest blood glucose measurements.

Providing a way to combine a person's health data and offering it in a way that can track the health of a person over time could be a solution to the previous problem and an advance in what is known as *Precision medicine*, moving from *Electronic Health Records* (EHR) to *Personal Health Records* (PHR) [11]. EHRs are computer records created and managed in healthcare systems by physicians, while PHRs are records that can be generated by physicians, patients, hospitals, pharmacies, and other sources and are managed by the patient.

The creation of health systems that are aware of a patient's health trajectory has been demanded by the fields of medicine and nursing for years [5]. Works like [7] [12] start to address this problem. However, as far as the authors know, there are no technical proposals that combines all the data from the different health related systems and processes it to provide it to software developers in an unified API.

In this paper, we propose a *Personal Health Trajectory API* (PHT API). With this API, healthcare application developers will be able to access a patient's health trajectory data and create applications with more complete and higher quality data, following the *data-driven medicine* approach. This approach argues that the use of the latest analytical techniques can lead to better health outcomes and help many more people.

To detail this proposal, the rest of the paper is structured as follows. In Sect. 2, the related works are described. In Sect. 3, the aims, objectives and research methodology of this work are detailed. Section 4 presents the current state of the work. And finally, Sect. 5 discusses the future work plan, alongside the conclusions.

2 Related Works

Looking at a patient complete health trajectory is not a new idea. For years, solutions to the above-mentioned problems have been demanded [5].

Due to this demand, some proposals have attempted to address this situation. In [7], H. La propose a framework for the collection of data from the user's own WoMT wearable devices and the use of that information to predict the probability of suffering certain diseases. A specific device is also proposed to integrate the different sensors needed to collect all the necessary data from the user. Simillarly, in [8], Moguel et al. propose to collect information about the adherence to pharmacological treatments by using their own WoMT device.

However, these works are focused on the incorporation of WoMT devices in diagnostics and forget the problem of information dismissal between different health systems. For this reason, in [12] Shameer et al. study the components and information that should be included in a system that tries to offer solutions oriented to people and not solutions oriented to health institutions.

Finally, the authors of this paper have been working in making systems aware of their users needs and preferences. Starting from the People as a Service paradigm [4], different frameworks and solutions have been proposed to simplify the interoperability between smart things and humans (like Situational-Context [2]). The authors have already taken advantage of these concepts in the development of health related solutions [9], and the work presented here is the next step in developing a virtual representation of the personal health trajectory of a user.

3 Research Aims, Objetives and Methodology

To implement our proposal, a number of issues will have to be addressed. The main objective will be to develop an API that provides access to the health trajectory of users. In order to achieve this, concerns like the interoperability of WoMT devices or the integration of data from different sources should be addressed. There are works in the literature that can help us address these concerns. In the area of data integration, works like [6] propose the use of blockchain technology to integrate the electronic health records of the user among different healthcare systems and WoMT devices; and [11] implements a PHR model that integrates distributed health records using blockchain technology and the openEHR [1] interoperability standard. To integrate the data from WoMT devices, Flores et al. propose a semantic web-based solution [3].

Starting from these works, the main scientific contributions of this proposal are focused on:

- **Distributed data integration**. This problem is not new in the field of information technology and there are different approaches to solving it [1]. In recent years the use of blockchain to store EHR [6] is expanding, so our solution should allow the integration of data from different blockchains and the interaction between them, creating a "blockchain federation".
- **WoMT device data flows**. The devices provide a continuous flow of data that can sometimes be interesting, but in other cases provide too much information. Process mining techniques will be used to filter and interpret this information collected from user devices.
- **Data enrichment**. Once integrated, patient data can be used to infer additional information that separately they did not give before. Data mining processes will be used to give greater expressiveness to the integrated "raw" data from different sources.
- **Personal Health Trajectory**. Orient the approach of the medical data to follow the health of a person along their life and offer this data through an API.

[1] https://www.openehr.org/.

To achieve the proposed objective, we are following the Design Science methodology, where researchers see an artifact as something that should support people in practice. The development of this work passes through different stages: (1) reviewing the state of the art of proposals for health systems oriented to the trajectory of people; (2) developing an architecture that allows us to offer an API to access a person's health data along their life; and (3) developing the API, which will allow to offer the advantages of the *Personal Health Trajectory*.

4 Preliminary Key Results or Contributions

Figure 1 shows the proposed architecture that would allow software developers to consult the integrated data through a single access point.

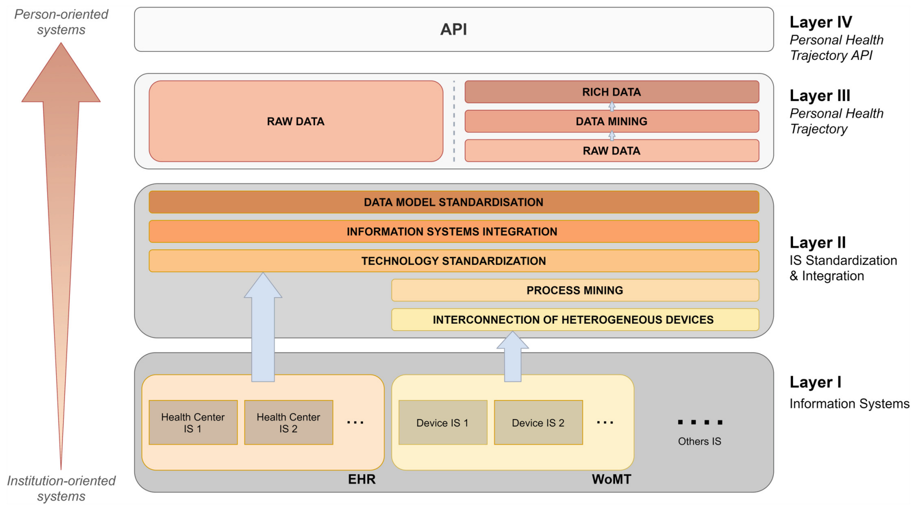


Fig. 1. Proposed architecture

This architecture is composed by software layers added over the current medical and WoMT devices information systems. An alternative solution, storing the information from the different system in a centralized repository, following a common ontology for data representation, could be explored. However, it would imply a greater compromise by healthcare institutions and manufacturers of WoMT devices, which can be difficult to achieve.

In general terms, the mission of each of the four main layers of the architecture is as follows:

- **Layer I: Information Systems.** Maintainer of patient data. It is composed by the current information systems.
- **Layer II: IS Standarization & Integration.** Responsible, firstly, for standardizing the information stored in the previous layer, including the use of different technologies and different data models; and secondly, for unifying the data of each information system. In the case of WoMT devices, it will also be responsible for their interoperability and the processing of the stored data streams.

– **Layer III: *Personal Health Trajectory*.** Responsible for providing health trajectory data for a person. This data may be provided "raw" (unprocessed) or with greater expressiveness, after applying Data Mining techniques on them.
– **Layer IV: *Personal Health Trajectory API*.** Responsible for providing a point of access to a person's health trajectory data to all those who want to develop software on *Personal Health Trajectory*.

5 Conclusions and Work Plan

Current health systems maintain patient records separately between their different information systems. The same applies to the user's WoMT devices. If a user or healthcare system wants to access all medical information along the patient's life, they do not have a way to find all this information together in a contrasted and organised manner.

To solve this problem, this paper proposes a *Personal Health Trajectory API*, which integrates the EHRs of the healthcare systems that the patient has visited and the data from their WoMT devices and offers them through a single access point.

The future work associated with this doctoral work is shown in Fig. 2 where some of the most important tasks are detailed. The initial version of the architecture has been done for the development of this paper.

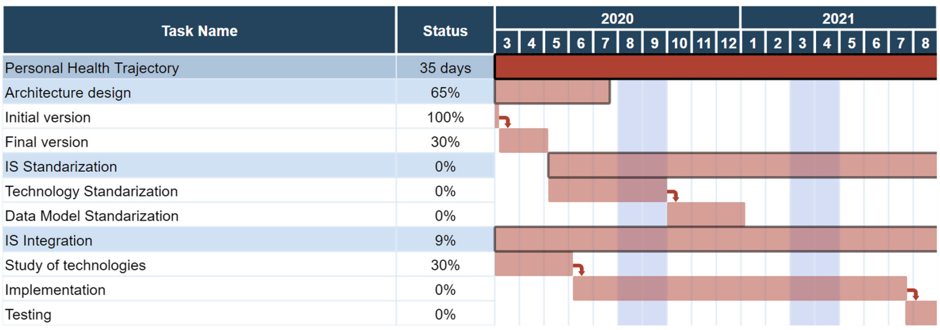


Fig. 2. Gantt chart

Acknowledgment. This work was supported by the project 0499_4IE_PLUS_4_E funded by the Interreg V-A España-Portugal 2014-2020 program, by the project RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

1. Open data for all: an API-based approach (interested?). https://modeling-languages.com/open-data-for-all-api/

2. Berrocal, J., Garcia-Alonso, J., Canal, C., Murillo, J.M.: Situational-context: a unified view of everything involved at a particular situation. In: Bozzon, A., Cudre-Maroux, P., Pautasso, C. (eds.) ICWE 2016. LNCS, vol. 9671, pp. 476–483. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-38791-8_34
3. Flores-Martin, D., Berrocal, J., Garcí-a-Alonso, J., Canal, C., Murillo, J.M.: Enabling the interconnection of smart devices through semantic web techniques. In: Bakaev, M., Frasincar, F., Ko, I.-Y. (eds.) ICWE 2019. LNCS, vol. 11496, pp. 534–537. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-19274-7_41
4. Guillén, J., Miranda, J., Berrocal, J., García-Alonso, J., Murillo, J.M., Canal, C.: People as a service: A mobile-centric model for providing collective sociological profiles. IEEE Softw. **31**(2), 48–53 (2014). https://doi.org/10.1109/MS.2013.140
5. Henly, S.J., Wyman, J.F., Gaugler, J.E.: Health trajectory research: a call to action for nursing science. Nurs. Res. **60**(3 SUPPL.), S79 (2011). https://doi.org/10.1097/NNR.0b013e31821cc240
6. Kassab, M., Defranco, J., Malas, T., Graciano Neto, V.V., Destefanis, G.: Blockchain: a panacea for electronic health records? In: Proceedings - 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare, SEH 2019, pp. 21–24. Institute of Electrical and Electronics Engineers Inc., May 2019. https://doi.org/10.1109/SEH.2019.00011
7. La, H.J.: A conceptual framework for trajectory-based medical analytics with IoT contexts. J. Comput. Syst. Sci. **82**(4), 610–626 (2016). https://doi.org/10.1016/j.jcss.2015.10.007
8. Moguel, E., Azabal, M.J., Flores-Martin, D., Berrocal, J., Garcıa-Alonso, J., Murillo, J.M.: Asistente de voz para el recordatorio de tratamiento farmacológico. Jornadas de Ingeniería del Software y Bases de Datos (JISBD) (2019)
9. Moguel, E., Berrocal, J., García-Alonso, J.: Systematic literature review of food-intake monitoring in an aging population. Sensors **19**(15), 3265 (2019). https://doi.org/10.3390/s19153265
10. Philip, N., et al.: Design of a restful middleware to enable a web of medical things. In: 2014 MOBIHEALTH, pp. 361–364, November 2014. https://doi.org/10.1109/MOBIHEALTH.2014.7015986
11. Roehrs, A., da Costa, C.A., da Rosa Righi, R., da Silva, V.F., Goldim, J.R., Schmidt, D.C.: Analyzing the performance of a blockchain-based personal health record implementation. J. Biomed. Inform. **92**, 103140 (2019). https://doi.org/10.1016/j.jbi.2019.103140
12. Shameer, K., Badgeley, M.A., Miotto, R., Glicksberg, B.S., Morgan, J.W., Dudley, J.T.: Translational bioinformatics in the era of real-time biomedical, health care and wellness data streams. Brief. Bioinform. **18**(1), 105–124 (2017). https://doi.org/10.1093/bib/bbv118
13. Stiell, A., Forster, A., Stiell, I., Van Walraven, C.: Prevalence of information gaps in the emergency department and the effect on patient outcomes. CMAJ **169**(10), 1023–1028 (2003). https://www.scopus.com/inward/record.uri?eid=2-s2.0-0344515549&partnerID=40&md5=a93a898d90f493d07542cf5aa9dd6542. Cited By 151

Appendix D

Time Series Forecasting to Predict the Evolution of the Functional Profile of the Elderly Persons

Authors: *Javier Rojo, Enrique Moguel, Cesar Fonseca, Manuel Lopes, Jose Garcia-Alonso, Juan Hernandez.*

Publication type: *International workshop paper.*

Workshop: *Third International Workshop on Gerontechnology.*

Year of publication: *2021.*

DOI: *10.1007/978-3-030-72567-9_2*

Time Series Forecasting to Predict the Evolution of the Functional Profile of the Elderly Persons

Javier Rojo[1], Enrique Moguel[1], Cesar Fonseca[2], Manuel Lopes[2], Jose Garcia-Alonso[1], and Juan Hernandez[1]

[1] University of Extremadura, Cáceres, Spain
{javirojo,enrique,jgaralo,juanher}@unex.es
[2] University of Evora, Évora, Portugal
{cfonseca,mjl}@uevora.pt

Abstract. There are many pathologies and capacity losses that progress with a similar evolution profile in certain groups of people. Health professionals are becoming increasingly knowledgeable in anticipating the development of these pathologies through preventive medicine. However, the increasing amount of data, coming from the collection of information from a larger number of patients, makes it difficult to analyse it manually. In the case of gerontology, it is difficult to classify in groups the evolution of the elderly for common pathologies in that age group. To be able to do this would make it possible to know in advance how a pathology or capacity loss will progress in an ageing person and to apply the corresponding preventive procedures. There are already works that try to improve the results of preventive medicine, but these are focused on analysing the current state of the patient and not their foreseeable future. In this article, time series forecasting by means of recurrent neural networks is used to analyse the evolution of the functional profile of ageing people as a time series. Based on the patterns contained in the patient's time series and in the training of a model with data from previous patients, it is possible to determine the future evolution in patients with a similar history. To do this, functional profile data collected on an assessment platform developed by the authors of this article is used.

Keywords: Preventive medicine · Medical informatics · Recurrent neural networks · LSTM · Time series forecasting

1 Introduction

With the increase of age, many patients develop pathologies and capacity losses common in the ageing population. Many of these pathologies and losses are progressive and show a similar evolution in people with similar characteristics [1]. Examples of these are dementia [2] or the deterioration of the functional profile of elders with time [3]. In particular, the latter is something that affects most of the ageing population.

J. García-Alonso and C. Fonseca (Eds.): IWoG 2020, LNBE, pp. 11–22, 2021.
https://doi.org/10.1007/978-3-030-72567-9_2

These capacity losses present, in many cases, common patterns of evolution in patients with similar characteristics [1]. This makes it possible for health professionals to anticipate the progression of the capacity loss and combat it as soon as possible. However, to classify each patient case manually is sometimes difficult (or even impossible). Specially, in environments where many patients are treated and there is a need to distinguish between different types of evolution for a given condition. Therefore, in many cases it is complex to anticipate how a patient will evolve and to apply preventive procedures.

To solve this problem, there are proposals that provide software for health professionals to process patient data in order to help with their diagnostics. In the field of preventive medicine, there are proposals that allow, based on a patient's health measurements at a specific moment, to determine if the person suffers from any illness [4,5]. For this purpose, Machine Learning and Deep Learning techniques are applied. However, these proposals use the patient's current state. They do not allow to infer how the patient's condition will evolve in the future to determine if they will suffer from the disease or capacity loss in question or how it will progress. Other proposals analyse, on a theoretical level, the use of deep learning to be able to analyse patient data like a time series and predict future values [6].

This article implements a deep learning model that, based on training with data of the already known evolution of patients as time series, allows the prediction of the future evolution of other patients in the use case of the deterioration of the functional profile of the elderly. The information provided by the development of the *Multidimensional Integrated Assessment Platform for elderly (MIAPe)* [7] is also used as background. From this platform we use the data of the deterioration of the functional profile of the ageing people and their evolution.

Thanks to this proposal it will be possible to determine the future functional profile's evolution of patients with similar conditions. This will allow the creation of personalized treatments for each patient at an earlier stage.

To develop this proposal, the rest of the article is structured as follows. Section 2 shows the works that motivate this proposal. Section 3, details the proposal indicating the data processing performed, alongside the model developed to determine the evolution of a patient based on previous data. Section 4 describes the case study and the results of the validation. In Sect. 5 future work is introduced to increase the scope of this project. Finally, Sect. 6 gives some brief conclusions.

2 Motivations and Related Works

Preventive medicine has a very important place in the field of healthcare. Health researchers are increasingly stressing the importance of augmenting the number of educational resources in this field [8,9]. However, the great variety of diseases (new or not) and the wide range of symptoms that each patient may present for the same disease, makes it difficult for health professionals to detect them at an early stage.

To help health professionals, there are many proposals that try to offer software that facilitate their work and complement their medical assessments. An example of this type is the proposal of Yu et al. [4] that uses supervised and unsupervised Machine Learning tools to generate predictive models. Thanks to these models, online health assessments are offered to patients and physicians. In this way, personalized and preventive care can be offered through telemedicine. Another type of proposal is that of Sabra et al. in [5], where they are focused on the importance for preventive medicine of analysing and classifying the medical characteristics of patients before offering this data to systems that make predictions. Furthermore, it proposes the use of a hybrid architecture, which makes use of these classified characteristics on various Machine and Deep Learning classifiers, offering stronger predictions.

However, although these and other solutions help to generate diagnoses that allow the detection of diseases that would be complex to detect by a physician without the help of the system, they are limited to work with the patient's health data collected until that moment. Therefore, they do not allow to anticipate the development of a condition, checking out how a condition will progress from that point ahead. Many conditions show a similar evolution in certain groups of patients. Therefore, it could be determined how patients are going to progress according to the evolution of previous patients who presented a similar condition [1]. To make this type of analysis on the evolution of a patient, time series can be used [10]. In this way, the evolution of the disease in a patient can be treated as a time series.

Among the time series analysis techniques, Time Series forecasting is used to predict future values based on previously observed values, with which a prediction model is trained. Examples of the use of this type of technique are the prediction of Meteorological Weather [11] or the prediction of the evolution of cases in pandemics [12]. In the field of health, Hirschfeld pointed out many years ago in [13] that analysing the time series generated by regular observations of patient's health would help in the management of chronic and progressive diseases or capacity losses. To do this, he proposed the use of forecasting techniques on the automated systems of his time. It is not a coincidence that authors such as Bhavya et al. have continued to work on proposals of this type, analysing in [6] the use of different Deep Learning techniques for the generation of prediction models in healthcare. Thanks to this analysis, they have concluded that the use of Recurrent Neural Networks (RNNs) and, specifically, the Long Short-Term Memory (LSTM) RNN, is the best way to analyse time-series medical data.

The solution proposed in this paper uses Time Series forecasting to predict the future values of the functional profile of the elderly based on the previously observed values. For this purpose, time series are generated with the parameters that measure the functional profile of the elderly and are analysed with RNNs, offering an automated analysis tool. The data collected by caregivers and nurses in MIAPe for the functional profile of different ageing people are employed as the starting point.

MIAPe is a platform for monitoring and grouping information about the health of the ageing population. For this purpose, the platform employs the concept of virtual profiles and the integration of health data from IoT devices [7]. Solutions to automate the interaction with these devices [14] are also being worked on. Thanks to the integration of the health data of an ageing person in this platform, it is possible to generate their *Personal Health Trajectory* [15].

3 Predicting Evolution Using Deep Learning

The solution presented in this paper is divided into two different parts. First, the acquisition and preparation of the data needed to train the deep learning model. Next, the definition of the deep learning model, using a LSTM RNN, for the time series forecasting.

3.1 Data Acquisition and Processing

The first step, before starting to define the model with which the time series forecasting will be performed, is to prepare the data to be used. To do this, the data that compose the functional profile of an ageing person has been collected, according to the functional profile evaluation method used in the MIAPe platform.

According to MIAPe, the functional profile of an elderly person is composed of five measures: (1) *overall score of functionality*, (2) *self-care*, (3) *learning and memory functions*, (4) *communication* and (5) *relationship with friends and caregivers*. The values of these measures are calculated with the value obtained for the three aspects evaluated in the *Elderly Nursing Core Set (ENCS)* [16] form: *body functions*, *body structure* and *ambiental factors*. So, knowing the numerical value obtained in each of these three aspects, the functional profile of the ageing person at any given time can be calculated.

Having the data of these three parameters for the evaluations that have been done until that moment, a time series is generated with the evolution of each parameter for each elder. This way, the evolution of the functional profile of an elderly is represented by three time series: one for each parameter. So, the aim is to predict the value that will be obtained in the next evaluation for each parameter, taking into account that the time between evaluations is equidistant.

In order to generate the time series of each parameter, it is necessary to collect the ordered values that have been obtained in the successive evaluations of an elderly person and store them in a structure that maintains this order. For the given implementation, the values have been stored in an array, so that each elder has a vector for each of their parameters (see Fig. 1). The values of these vectors are those given to the prediction model for training. At the time of forecasting with the trained model, the values of the three time series (one per parameter) of the new elder must be provided as input to the model in the same format.

Elderly Number	functions	structures	ambiental factors
0	[12, 12, 12, 12, 12, 33, 28]	[67, 70, 63, 52, 50, 55, 83]	[33, 33, 33, 27, 27, 53, 20]
1	[40, 22, 40, 17, 22, 17, 20]	[95, 82, 95, 65, 82, 68, 58]	[87, 67, 87, 80, 80, 60, 60]
2	[22, 23, 17, 17]	[68, 68, 52, 42]	[67, 60, 60, 60]
3	[13]	[52]	[53]
4	[27]	[100]	[60]

Fig. 1. Dataframe that store the time series of the functional profiles.

3.2 LSTM's Model for Time Series Forecasting

The model used to make the type of predictions proposed in this paper (time series forecasting) is a Recurrent Neural Networks (RNNs) model. A neural network of this type is employed because of its ability to maintain data memory. This means that its neurons have feedback, taking the outputs obtained with previous inputs as new inputs. Thanks to this, long data sequences can be analysed step by step. In particular, between the different types of RNNs, the use of the Long Short-Term Memory (LSTM) is chosen. This type of RNN has a better long-term memory than classic RNNs.

After selecting the type of model to be used, each of the sub-sections that had to be considered for the definition of the model are discussed below.

Type of Forecasting. When a model for this type of analysis is defined, it is also important to define what type of time series forecasting is being done. Specifically, it is carried out a type of forecasting known as Multivariate Forecasting, due to the fact that, for a specific time mark in the evolution of the data, there are more than one observation (one for each of the three parameters/time series used). Specifically, within Multivariate Forecasting, this is a Multiple Parallel Series problem because, at the moment of predicting it is necessary to calculate a new value for each of the parameters/time series that are used as input. So, there are as many outputs as inputs.

Inputs and Outputs. It is also essential to define which are the inputs and outputs of the model. In the case of outputs, the model must predict three numerical values (one per parameter of the functional profile). This is a regression problem (not a classification one, as it is often the case with neural networks), so the output values will be continuous values (not discrete).

As input, the three time series representing the evolution of the patient's functional will be taken. However, there is no type of RNN that supports a time series (coded as a vector, for example) of variable size as input. The input that is given to the model must be of a fixed size. As not all the elders have the same amount of evaluations and this number is changing (increasing) over time, the solution is to send to the model a fixed amount of the last samples of the time series. This amount must be defined and this data is the one used to calculate the output of the model. In this case, because there are few elderly people with many evaluations in the dataset, only the last two samples of each time series that make up the evolution of the elderly person are taken as inputs. This number of samples is small but enough for the proposal presented in this paper. For the application of this proposal in a real environment, a greater number of samples would be required.

In this way, to be able to analyse the full evolution of an elderly person, each of their time series will be fragmented into overlapping fragments of three values, for training (two input and one output), and of two values, for predictions (two input). For example, a person with 6 evaluations will generate 4 such fragments for training and one fragment with the two last values to predict the next value with the model.

Predictions. To predict new values, for each time series delivered as input to the model, an array with two (ordered) values from this time series must be given to it. With these values and the learning obtained, the model gives as output a new value for each of the time series to which the values belong. In this way, the model is offering the next value of each time series or, what is the same, the predicted value of each parameter in the next evaluation of the elder.

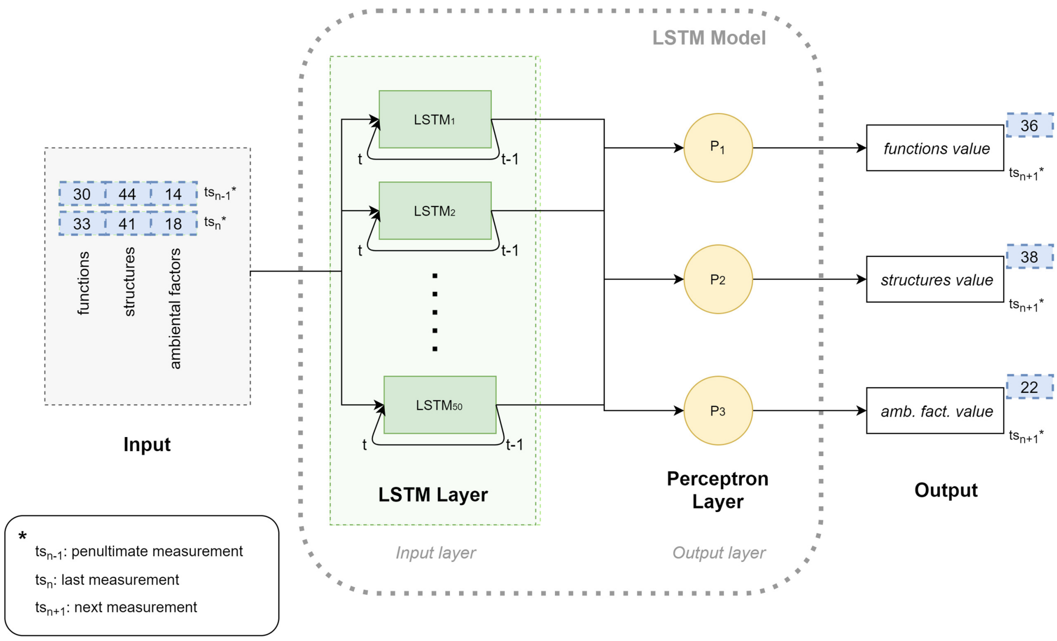


Fig. 2. Structure of the LSTM's model

Structure of the Neural Network. After defining the type of network used and its inputs and outputs, Fig. 2 shows the structure of the implemented neural network. This network is composed by only two layers: an LSTM layer as input and a simple perceptron layer as output.

The LSTM layer is the one that makes this model a RNN. When the problem to resolve is not too complex, the use of only one LSTM layer is the best option [17]. In this case, it is a stateless LSTM layer, which does not hold memory from one batch to another. This type of LSTM's configuration is chosen because in the training dataset the fragments of the time series of all the elderly people are combined, in order to improve the generalization of the model, to predict the evolution of an elderly person based on the evolution of others. If it were a stateful LSTM, the neurons of this layer would keep in memory the results obtained with the previous training fragments. This gives very good results when the training is based on only one time series (in this case, if only the three time series of one elder were used to train the model). This layer is composed of 50 neurons with *relu* activation. The number of neurons has been adjusted based on the validation data. The activation function used has been selected because it offers better results in terms of learning, but it has the problem that it can flatten the volatility of the time series. In this case, by using few values as input, flattening the volatility is not a problem. Finally, this network takes 6 parameters as inputs (two measurements of each of the three time series of evolution).

The next layer is a simple perceptron layer, as used in MLP neural networks. This layer is used to transform the output of the 50 LSTM neurons of the previous layer into the 3 numerical values to be predicted. As activation, a linear function f(x) = x is used, so that it returns as output the value obtained directly by each neuron. This is a regression problem, where it is necessary to calculate continuous values and not to classify them into discrete values.

Training Parameters. To train the model, it is necessary to define another set of parameters. First, the loss function to evaluate if the model is learning and the degree of it. In this case, the Mean Square Error (MSE) function has been used, one of the most used loss function for regression problems. The optimization function is another of the parameters to be defined. It has been evaluated the choice of Adam or RMSprop, two of the most used ones. Although both are based on Stochastic Gradient Descent, the Adam function is better than RMSprop in terms of performance. Therefore, Adam will be used, together with a learning rate of 0.0002, adjusted based on the loss and accuracy function. And, finally, the number of epochs to train, which has been fixed at 400. The reason behind choosing these values of learning rate and number of epochs will be discussed in Sect. 4.

To conclude this section, it is important to mention that the value of some of the parameters discussed have been adjusted according to the data employed to the validation. The use of a different dataset would imply that parameters such as the number of layers and neurons should be adjusted. The learning rate and the epochs would also have to be adjusted again if data changes.

4 Validation

In order to validate the solution presented in this article, a validation phase has been carried out. Data about the accuracy of the system and the quality of the training has been collected using a dataset from the MIAPe platform.

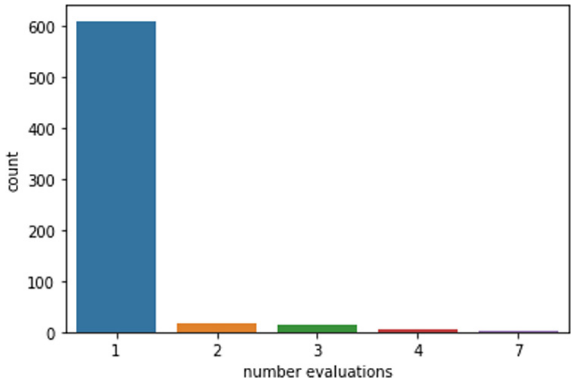


Fig. 3. Graphic related to the number of evaluations per elderly

4.1 Case Study

The case study used for the validation is the same introduced along this paper. The data of the elderly's functional profile collected by the MIAPe platform have been used. This functional profile is composed by five indicators, calculated from three measures that are evaluated by the elderly carers through the *Elderly Nursing Core Set (ENCS)* form.

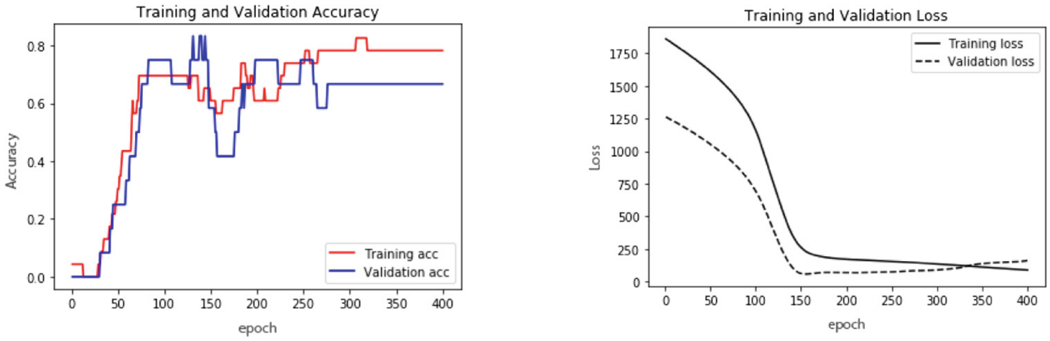
In total, MIAPe stores the data of approximately 1300 patients. Of these, 647 have at least one functional profile assessment. There are 720 functional profile assessments belonging to these 647 different elderlies. Therefore, it can be deduced that most of the elderly have only one assessment, so their data will not be optimal to the proposal of this paper. To check this, the distribution of the number of assessments per elderly can be seen in Fig. 3. Only 22 ageing people have 3 or more evaluations (minimum number of evaluations required for their evolution to be used on the training of the proposed system).

4.2 Results and Discussion

With the data collected from the case study, the model developed in the proposal has been evaluated. For this purpose, the accuracy obtained (Fig. 4a) and the format of the loss function (Fig. 4b), which evaluates the learning of the model, have been measured. This way, with the data represented on the two charts of Fig. 4, a series of conclusions can be extracted.

Thanks to the accuracy chart, it can be seen that the model is trained without overfitting, except in the last few epochs. If the loss chart is looked for those last epochs, it can be seen that this overfitting occurs at the moment the model starts to learn the training data "by memory", achieving lower losses than with the validation set (as opposed to before the overfitting). Having a model with too many epochs can lead to such a situation. Especially in cases where there are problems with the data. In this case, they are insufficient.

In order to situate the magnitude of the above statement, it is necessary to indicate that the dataset only contains data from 22 elderly people, which with their data allow the generation of 35 records from three evaluations.



(a) (b)

Fig. 4. Results of training with case study's data for (a) accuracy and for (b) loss.

Of these 35 records, 23 are used for training and 12 for validation. Any model of Machine Learning needs more data to be able to train correctly. In particular, Deep Learning models, such as this neural network, need even more data to train.

In addition to testing the final combination that gave the results shown in the figure above, other configurations were also tested, which allowed the exploration of how the results varied according to the number of layers, the activation function and other parameters that are commented on below.

First, it has been tried to modify the structure of the model. The first thing that has been adjusted is the number of LSTM layers. A configuration with two layers has been tested. However, it increased the complexity of the model, reaching an overfitting situation earlier and causing a worse training. In the LSTM RNN it is common to use one LSTM layer for simpler problems and two LSTM layers for more complex problems [17]. Configurations with more LSTM layers are not usually common, so they were discarded. As next step, the number of neurons in the LSTM layer has been adjusted. Different configurations have been tested. From 20 neurons per layer to 100. Finally, 50 neurons were chosen, as the results did not change much. Furthermore, the use of 100 neurons generates a model with unnecessary complexity (at least with the current amount of data) and therefore more susceptible to overfitting.

With regard to the learning rate, an effort has been made to adjust it based on the accuracy and loss function through the epochs. Although the value chosen is the one that gave the best results, a learning rate totally optimal and that generate a correct learning has never been achieved. This is clearly due to the amount of data because, by looking at the Fig. 4b, it can be seen that the loss function starts with a very small decrease (as if the learning rate was low) and in the subsequent epochs it decreases suddenly (as if the learning rate was high). Thanks to this, it is known that, with the current data, it will never be possible to obtain a learning rate that leads to correct learning.

Focusing now on the number of epochs, it has not been possible to determine an appropriate number because of insufficient data. A high number has been set to show the oscillation that occurs in the accuracy of successive epochs and how the loss function decreases. For the batch size, the default value of keras (32 samples) has been left, because, for the amount of data available, adjusting the batch size will not bring any benefit. When the amount of data will be greater, the batch size should be adjusted on the basis that if it is very low there will be noise in the loss function (depending on the bias of the data also) and if it is very high the model will not learn correctly.

As discussed in the process of adjusting the most training parameters, there are several indicators that show that the amount of data is small. Another indicator that has been found is that, although the training and validation sets are always split in the same way, the results that are obtained if the model is trained several times vary for each of these trainings.

It is also important to remember that the actual model is trying to determine the next evaluation based on only 2 evaluations. Therefore, obtaining a high probability of success is difficult (and even less if there are more different patients). If there would be enough data to be able to train a model that predicts based on more assessments, the accuracy would probably increase.

5 Future Works

Having defined everything that has been done so far, it is easy to see that the main future work is to obtain sufficient data to validate the proposal set out in this article.

However, by the time this happens, two lines of research have already been identified for continue working and improving the current proposal.

Determining Using Groups of Patients with Similar Evolution. When the number of different patients with evaluations increase, integrate the data of very different patients, with very different evolution, would make the model need a lot of data to learn correctly and could still decrease its performance. To solve this, the development of a system that, by applying other patient characteristics (e.g. age, weight or gender), allows the generation of groups with similar evolution is proposed. In this way, patients would be classified in these groups and an independent model would be generated for each group.

Automatic Model Adjustment and Learning. The proposed prediction model is used in a dynamic environment, where the amount of data is constantly growing (new patients and new assessments). Because of this there will be certain situations when the network parameters will have to be adjusted to adapt the model to the new complexity of the problem. Being able to automate this process would help to always maintain a model that offers high-quality predictions.

6 Conclusions

This paper proposes the development of a deep learning model that, by using time series forecasting, allows the analysis of the evolution of the functional profile of ageing people. In this way, automated predictions will be offered of how the functional profile of an elderly person will advance in the near future, based on their evolution to date and that of patients with a similar more advanced evolution.

This solution brings benefits to the proactivity of preventive medicine, helping health professionals to create diagnoses for patients by having a vision of how expect the patient will evolve in the near future. In addition to the functional profile of the elderly, a solution of this type can be extended to the analysis of any progressive capacity losses or pathology, which can be analysed using the evolution presented by the patient.

In order to validate the proposed model, it has been used the data of the functional profile of the elderly stored in the *Multidimensional Integrated Assessment Platform for elderly (MIAPe)*, developed by members of the research team to which the authors of this article belong. However, the amount of data available is still too small to affirm with complete certainty the validity of the proposed model.

In this way, a series of future improvements have been proposed which would improve the results obtained by the proposal, when sufficient data are available to evaluate it.

Acknowledgements. This work was supported by the project 0499_4IE_PLUS_4_E funded by the Interreg V-A España-Portugal 2014–2020 program, by the project RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

1. Wang, Y., Zhou, X., Noulas, A., Mascolo, C., Xie, X., Chen, E.: Predicting the spatio-temporal evolution of chronic diseases in population with human mobility data. In: IJCAI International Joint Conference on Artificial Intelligence, July 2018, pp. 3578–3584. International Joint Conferences on Artificial Intelligence (2018). https://doi.org/10.24963/ijcai.2018/497
2. Flicker, C., Ferris, S.H., Reisberg, B.: Mild cognitive impairment in the elderly. Neurology **41**(7), 1006–1006 (1991). https://doi.org/10.1212/WNL.41.7.1006. https://n.neurology.org/content/41/7/1006
3. Jacobs, J.M., Maaravi, Y., Cohen, A., Bursztyn, M., Ein-Mor, E., Stessman, J.: Changing profile of health and function from age 70 to 85 years. Gerontology **58**(4), 313–321 (2012). https://doi.org/10.1159/000335238. https://www.karger.com/Article/FullText/335238
4. Yu, C.S., Lin, Y.J., Lin, C.H., Lin, S.Y., Wu, J.L., Chang, S.S.: Development of an online health care assessment for preventive medicine: a machine learning approach. J. Med. Internet Res. **22**(6) (2020). https://doi.org/10.2196/18585
5. Sabra, S., Malik, K.M., Afzal, M., Sabeeh, V., Charaf Eddine, A.: A hybrid knowledge and ensemble classification approach for prediction of venous thromboembolism. Expert Syst. **37** (2020). https://doi.org/10.1111/exsy.12388

6. Bhavya, S., Pillai, A.S.: Prediction models in healthcare using deep learning. In: Advances in Intelligent Systems and Computing, AISC, vol. 1182, pp. 195–204. Springer (2019). https://doi.org/10.1007/978-3-030-49345-5_21. https://link.springer.com/chapter/10.1007/978-3-030-49345-521
7. Moguel, E., Berrocal, J., Murillo, J.M., Garca-Alonso, J., Mendes, D., Fonseca, C., Lopes, M..: Enriched elderly virtual profiles by means of a multidimensional integrated assessment platform. Procedia Comput. Sci. **138**, pp. 56–63 (2018). https://doi.org/10.1016/j.procs.2018.10.009
8. Shi, H.Y., Wang, S.Z., Yang, X.J., Lin, L., Hu, J.Y.: Preventive medicine curriculum system in training program of clinical medicine in the era of Healthy China. Zhonghua liu xing bing xue za zhi = Zhonghua liuxingbingxue zazhi **41**(7), 1155–1159 (2020). https://doi.org/10.3760/cma.j.cn112338-20200104-00009
9. Liu, Y., Jin, G.F., Wang, J.M., Xia, Y.K., Shen, H.B., Wang, C.Q., Hu, Z.B.: Thoughts on the reform of preventive medicine education in the context of new medicine. Zhonghua yu fang yi xue za zhi [Chin. J. Prev. Med.] **54**, E030 (2020). https://doi.org/10.3760/cma.j.cn112150-20200328-00461
10. Wei, W.W.S.: Oxford Handbooks Online Time Series Analysis, vol. 2, March 2013. https://doi.org/10.1093/oxfordhb/9780199934898.013.0022. https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199934898.001.0001/oxfordhb-9780199934898-e-022
11. Ramos, M.M.P., Del Alamo, C.L., Zapana, R.A.: Forecasting of meteorological weather time series through a feature vector based on correlation. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), LNCS, vol. 11678, pp. 542–553. Springer, September 2019. https://doi.org/10.1007/978-3-030-29888-3_44
12. Tomar, A., Gupta, N.: Prediction for the spread of COVID-19 in India and effectiveness of preventive measures. Sci. Total Environ. **728** (2020). https://doi.org/10.1016/j.scitotenv.2020.138762
13. Hirschfeld, W.J.: Forecasting and chronic illness. Bull. Math. Biophys. **33**(3), 425–437 (1971)
14. Rojo, J., Flores-Martin, D., Garcia-Alonso, J., Murillo, J.M., Berrocal, J.: Automating the interactions among IoT devices using neural networks. In: 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), pp. 1–6 (2020)
15. Rojo, J., Hernandez, J., Murillo, J.M.: A personal health trajectory API: addressing problems in health institution-oriented systems. In: Bielikova, M., Mikkonen, T., Pautasso, C. (eds.) Web Engineering, pp. 519–524. Springer, Cham (2020)
16. Goes, M., Lopes, M., Oliveira, H., Marôco, J., Fonseca, C., Santos, M., Caeiro, J.: Psychometric qualities of a core set to ascertain the functional profile of Portuguese elderly citizens. In: García-Alonso, J., Fonseca, C. (eds.) Gerontechnology, pp. 314–329. Springer, Cham (2020)
17. Reimers, N., Gurevych, I.: Optimal Hyperparameters for Deep LSTM-Networks for Sequence Labeling Tasks, July 2017. http://arxiv.org/abs/1707.06799

Appendix E

Blockchains' federation for integrating distributed health data using a patient-centered approach

Authors: *Javier Rojo, Juan Hernández, Juan M Murillo, Jose Garcia-Alonso.*

Publication type: *International workshop paper.*

Workshop: *2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH) - Collocated with the International Conference on Software Engineering (ICSE) (2021 GGS Class 1 Core A++).*

Year of publication: *2021.*

DOI: *10.1109/SEH52539.2021.00016*

2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH) | 978-1-6654-4458-3/20/$31.00 ©2021 IEEE | DOI: 10.1109/SEH52539.2021.00016

Blockchains' federation for integrating distributed health data using a patient-centered approach

Javier Rojo*, Juan Hernández *, Juan M. Murillo* and Jose Garcia-Alonso*
*University of Extremadura
Caceres, Spain
Email:{javirojo, juanher, juanmamu, jgaralo}@unex.es

***Abstract*—Today's world is a globalized and connected one, where people are increasingly moving around and interacting with a greater number of services and devices of all kinds, including those that allow them to monitor their health. However, each company, institution or health system usually store its patients' data in an isolated way. Although this approach can have some benefits related with privacy, security, etc., it also implies that each one of them generates different, incomplete and possibly contradictory views of a patient's health data, losing part of the value that this information could bring to the patient. That is the reason why researchers from all over the world are determined to replace the current institution-centered health systems with new patient-centered ones. In these new systems, all the health information of a patient is integrated into a unique global vision. However, some questions are still unanswered. Specifically, who should store and maintain the information of a given patient and how should this information be made available for other systems. To address this situation, this work proposes a new solution towards making the Personal Health Trajectory of patients available for both, the patients themselves and health institutions. By using the concept of blockchains' federation and web services access to the global vision of a person health can be granted to existing and new solutions. To demonstrate the viability of the proposal, an implementation is provided alongside the obtained results in a potential scenario.**

***Index Terms*—Data integration, health data, Blockchain, permissioned blockchain, Web Services**

I. Introduction

The digitalization of health information systems is a reality that has been present for years. Different health institutions have been digitizing their patients' health records and offering them as Electronic Health Records (EHRs) [1]. Over the years, and with the undeniable penetration that Internet of Medical Things (IoMT) [2], [3] devices have had among users, these EHRs have been enhanced with information coming from these devices. In recent years, this has resulted in an evolution from the term EHR to the broader term Personal Health Record (PHR) [4], which includes any patient's health data; not just those generated and managed in healthcare systems by physicians.

All this digitalization has helped institutions to keep their patients' data organized and presenting a great value for the institution and for the patients themselves. However, due to the globalization of society and the growing number of health solutions, there are more and more institutions and services with which a patient interacts throughout their life [5].

With the current institution-centered health information systems, this is a problem. The data of a single patient is scattered among the different services of the IoMT devices and health institutions with which they interacts throughout their life. Although this is positive for the institutions, since they have control over the health information they generate, at the same time it implies that there are different representations of a patient's health reality potentially inconsistent between them. In other words, the benefit that these systems generated before for the patient is now mitigated, since the different representations of the same reality make it impossible to have a single global representation of their health: their *Personal Health Trajectory* [6]. The creation of health systems that are aware of a patient's health trajectory has been demanded by the fields of medicine and nursing for years [7].

To try to solve this problem, an increasing number of studies are trying to give an alternative to the current institution-centered methods of storing patient data. These solutions are patient-centered and try to store each patient's information in a single data structure, with which all institutions and services that treat the patient will interact [8]–[11]. For the implementation of this structure, technologies such as blockchain [12]–[14] are commonly chosen. Blockchain is shown as the most promising technology, due to its distributed nature, as well as its guarantees on data security and privacy [15]. However, these proposals are still far from being adopted by the different health institutions, due to the fact that there are unresolved issues, such as the definition of who should keep this data structure alive and who is in charge of granting access to it [15]. In addition to these issues, with today's solutions, it is not easy to develop patient-centered health applications because the unique, global health reality is not accessible, limiting innovation and harming patients.

This paper offers a new patient-centered solution that not only provides the advantages of current solutions, but also addresses their weaknesses. For this purpose blockchain technology is used, similarly to existing proposals. However, a more complex architecture has been defined over the concept of one blockchain per patient, which involves the use of blockchains' federation and web services.

Thanks to this proposal, and as demonstrated through the implementation and validation shown in this paper, the integration of patient data is achieved without compromising access to the single global representation of their health by institutions

978-1-6654-4458-3/20/$31.00 ©2021 IEEE
DOI 10.1109/SEH52539.2021.00016

and services, facilitating the development of *Patient Health Trajectory*-aware software and making the transition from actual institution-oriented systems to the new patient-oriented systems closer. In conclusion, the work carried out throughout this paper allows us to offer the *Personal Health Trajectory* of a patient and makes it useful for both patients and the health professionals who care for them.

In order to present the work done, the rest of the document is structured as follows. Section II shows the motivations of this work and related work. Then, Section III describes the proposed solution based on blockchains' federation and the use of web services. Section IV details the validation performed to evaluate the proposed solution. Section V brings a brief discussion over the results obtained until now. Finally, in Section VI the conclusions of this work and some future lines of research are exposed.

II. Motivations and Related work

In the way health systems are conceived today, each health system maintains its patients' data stored in its own information system. When a new patient arrives at a health system, they are registered in the information system and any data produced by the successive interactions they have with that health system will be added. This data is not conditioned by or aware of the data stored by other health systems of their interactions with the same patient. In this way, an isolated representation of each patient in each health system is maintained.

These partial representations of the patient are a problem to be able to offer the best treatment for a patient, since diagnoses are never being offered on the total reality of their health. The problem grows at the same time as the number of services that are generating health data for a patient grows.

To better exemplify the problems this entails, the scenario of Paula is presented. *Paula is a Spanish women who suffers from diabetes. She is also a travel enthusiast. On one of her trips to China, Paula suffers a fainting spell due to hypoglycemia. She is treated in a health center in China, where her blood glucose levels are measured. However, when Paula returns to Spain, she cannot give the data of those measurements to her usual doctor, because they have been registered in the Chinese health system. Something similar happens with her smart glucometer. Only a few of the measurements she takes at home are transcribed to her health record. If Paula has another fainting spell, her doctor cannot access Paula's latest blood glucose measurements nor the ones from the previous episode.*

Providing a way to integrate a patient's health data and offering it in a way that can track the health of a patient over time can be a solution to the previous problem. This integration can be done by physically integrating the data on the same storage media or by providing a single access point for distributed data that makes it interoperable. In either case, a single, universal vision of the entire health reality of the patient is obtained.

In the first type of solution, there are proposals such as that of Spil et al. [8] or that of Kyazze et al. [9], which propose the use of a client-server architecture to store and to consult patients' health data. For this purpose, the first one make use of the Microsoft HealthVault platform, while the second one implement its own architecture called healthTicket. The problem with this type of proposals is that they are very intrusive for health institutions, since they require all institutions to migrate their data to a single repository. In addition to the security and privacy problems that can arise from having all the data in the same repository.

In order to offer less intrusive solutions, researchers such as Zhang et al. propose a client-server architecture [11], but this time using data from distributed repositories managed by different health institutions and services. Its architecture offers unique access to all this distributed data thanks to the use of a data collection layer and a data management layer, which integrate user data and make them interoperable. Thanks to this, integration is achieved without the need for institutions to migrate their data, although the security problems of the previous proposals remain. There is a single central repository, which makes it a unique point of fault and a point of interest for malicious attacks.

However, if instead of using a client-server architecture to generate the access point, a distributed technology such as blockchain is used, the problems previously mentioned are solved. That is why this technology is used in multiple proposals, such as of Roehrs et al., that propose the use of a blockchain per patient [12], which stores references to their different PHRs, stored in the institutions and services that generate it. Another proposal of this type is that of Cichosz et al. [13], although focused on the integration of diabetes data. At the same time, MedBlocks [14] by Fan et al. proposes a solution similar to the previous one, but also addressing the lack of a standard data management and sharing policy presented by Electronic Medical Records (EMRs), a more primitive representation than the EHRs or PHRs on which the rest of the proposals are focused.

As can be seen in the previous proposals, the use of blockchain is a step forward in the integration of distributed health data. However, this type of proposal is not free of discussion either. The most important problem is having to manage who owns the structure that maintains this global vision. Normally, the patient holds this role, since data belongs to them. This implies that institutions that want to make use of that global vision of their health will need that the patient gives them permissions to use it. In the case of having to attend a patient in an emergency situation, the patient may not be able to give access to the healthcare professional who is treating them. This limits the effectiveness of the treatment, since the healthcare professional does not have access to data. At the same time, and also due to the fact that access to the global vision of a patient's health is not easy for institutions and services, the development of software that consumes this global vision is complex in many cases. The existing solutions do not offer in many cases a simple way to develop applications and systems that consume the integrated data of a patient.

The proposal of this paper solves these problems, thanks to the concept of blockchains' federation and the use of web services. A single access point for distributed data is proposed, since the data remains stored in the institutions that generate it, but is organized through a structure that allows access and ensures the interoperability of distributed data.

The blockchains' federation concept is related to proposals such as multi-chain [16] where the use of a router blockchain to make interoperable a series of lower-level blockchains is proposed. However, these proposals are focused on inter-blockchain communication and increasing the throughput of operations over a single blockchain and provides no improvement for duplications or inconsistencies in the users information. In this case, in the patients information.

III. Blockchains' federation and its application to patient-centered health systems

The solution proposed in this paper offers unified access to distributed data grouped by patient. For this, an architecture based on blockchains' federation and web services is implemented. This architecture allows the connection with external health applications, which will consume the data through a REST API or a connector. This facilitates the development of health applications that use the *Personal Health Trajectory* of the patients.

As this solution is mainly based on blockchain, it is important that the reader knows at least some previous blockchain concepts, such as block and node. In blockchain, data is stored in an immutable chain of blocks, where blocks are in charge of store the information —being the chain of blocks the complete set of information—. Each user access this blockchain throughout a node. The nodes are inter-connected between them using a peer-to-peer network. Each of them maintains an complete copy of the blockchain, identical and shared by all the nodes in the network.

A. Blockchains' federation

The concept of blockchains' federation, as shown in Figure 1, refers to the interconnection of several lower-level blockchains (patients' blockchains) using another blockchain at the top (main blockchain) which is in charge of nesting them and providing access to all lower-level blockchains.

The patients' blockchains are in charge of saving the information in the system. Each patients's blockchain is self-contained and can be considered and employed as a data structure independent of the federation. The key of the blockchains' federation concept is that each of these blockchains stores the information of one patient. In the case of this proposal, each patient has all their health information, their *Personal Health Trajectory*, organized in a blockchain. Patients can interact directly with their *Personal Health Trajectory* through their blockchain.

To ensure that there are not several partial versions of a patient information in the different institutions and services, each patient must have only one blockchain. In addition, it is necessary to have a mechanism to allow the institutions and services that operated with the data to locate the blockchain of the patient for whom they want to read or write new data. The easiest way to achieve all this is to have a structure that indicates where the blockchain of each existing patient is located. This structure must be shared by all institutions and services. If each of them has its own independent structure to locate the patients' blockchains, the problem is still to ensure that all of them have the same location for the blockchain of one particular patient.

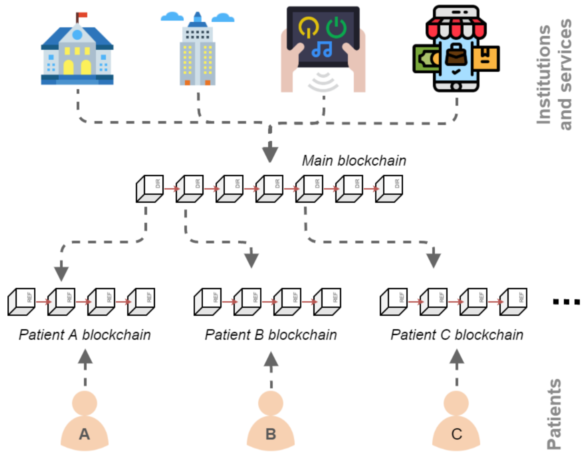


Fig. 1. Blockchains' federation

In blockchains' federation, this routing structure is implemented with another blockchain: the main blockchain. Each block in this blockchain stores the location of a patient's blockchain, as well as the information needed to identify the patient to which it belongs. Each institution has one node of the main blockchain, so that any change in the patients or in the location of their blockchains is noted by all institutions and services in the system.

While patients are not aware of the main blockchain and do not interact with it, the institutions and services that produce or consume data for these patients always access the patients' blockchains through it.

B. Architecture

Using the concept of blockchains' federation presented and web services, the architecture shown in Figure 2 is proposed. This architecture addresses the problem of distributed health data integration discussed above, solving the principal limitations of single blockchain proposals while maintaining their advantages. This is mainly thanks to the use of the federation and its main blockchain, which allows the location and access to the patients' data —stored in the patients' blockchains— to the institutions and services authorized to use it. In this way, even if a patient is treated urgently and cannot give access to their data, health professionals are able to access them through

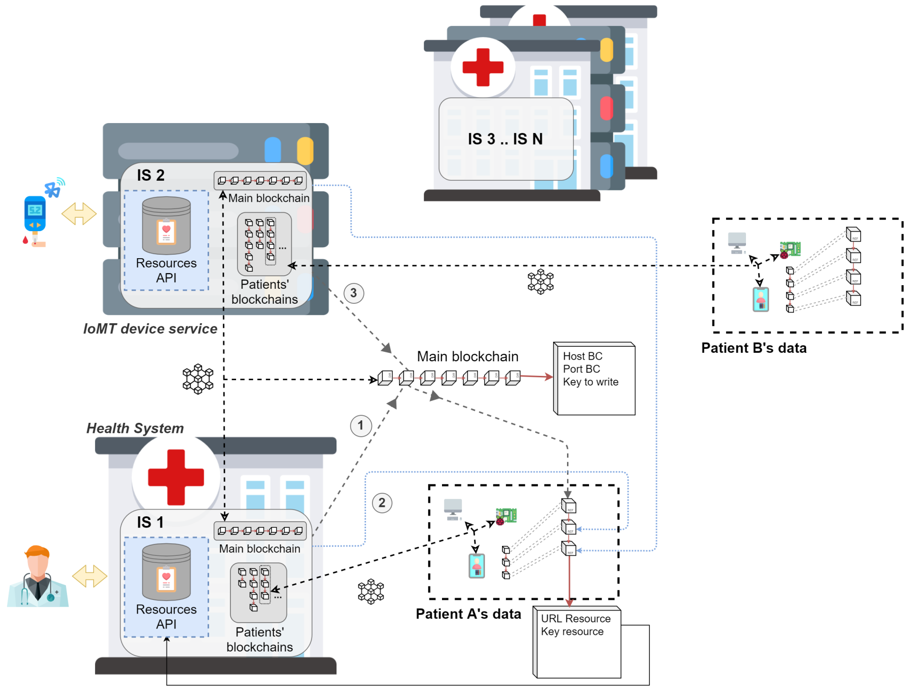


Fig. 2. Proposed architecture

the main blockchain, as long as their institution belongs to those that integrate their patients' data.

One of the main components of the architecture is the patients' blockchains. The information they store is private which should only be read and can be created by authorized entities. That's why these blockchains will be permissioned blockchains.

One of the problems noted in previous proposals about the use of blockchain to integrate patient health data was defining who was in charge of keeping a patient's blockchain alive and accessible. In this proposal, the main health institution to which a patient belongs at a given time is in charge of maintaining at least one node of the patient's blockchain. If the patient changes of main health institution, the new one must deploy a new node of the patient's blockchain. The old one can delete its node at that moment. Additionally, the proposal allows users to have a node of their own blockchain in one of their devices at any time, empowering them with greater control of their *Personal Health Trajectory* and allowing them to extract additional value from it.

As with the other proposals that do not physically integrate the patients' health data, but make them interoperable through a mechanism of references to where the information is actually stored, these patients' blockchains do not directly store the patients' health information. Instead, each block of these blockchains stores a reference to where the health information representing that block is stored. To facilitate this referral system, a Resources APIs is defined. Each healthcare institution and service, in its information system (labeled IS in the figure) deploys a Resources API, as a web service. This Resources API store health data generated at that institution or by IoMT devices using that service, for any patient in the system. Each time a new health record is added, a URL and key to access it is generated. This URL and key is stored in the blockchain of the patient to which the added health record belongs. This proposed storage system can be easily replaced by any other one, including the current ones in use by most health information systems, as long as they allow to reference the information in a similar way as it is done with the Resources API.

The last component that is involved in this architecture is the main blockchain. In this architecture, the main blockchain is used to locate the blockchain of each patient by the different institutions and services with which they interact. For this purpose, this main blockchain is shared by all of them. Each one of them must have a node of the main blockchain deployed, with which the health professionals of the institutions or the IoMT devices that use the service in question will interact. This blockchain is the component that unifies and ensures that, instead of having several partial views of a patient's health trajectory, there is a single *Personal Health Trajectory* with all the data of that patient. For its implementation, a permissioned blockchain will be used, such as for patients' blockchains. Only entities with enough permissions should be able to access the blockchain to locate the address of the *Personal Health Trajectory* of the different patients.

Figure 2 shows the steps that members of the institutions and the services that integrate the data must take to interact with the *Personal Health Trajectory* of a patient. When they want to add or read data from a patient that belongs to the same institution, (1) they employ the main blockchain node of their IS to locate where the patient's blockchain is deployed, and, after locating it, (2) read or write to it. These operation can be similarly performed when the patient does not belong to the same institution. When this happens, instead of creating a new profile or blockchain for the patient with the problems of duplication and inconsistencies already mentioned, they will (3) locate the patient existing blockchain through the main blockchain node of their institution's IS and operate with it.

In the case of being the patients who want to interact with their *Personal Health Trajectory* directly, the process is considerably simplified. Patients are not aware of the existence of the main blockchain, since they will interact directly with their blockchain, through the node maintained by their main institution or through another node they can maintain on one of their devices.

C. Implementation

The implementation of the proposed architecture depends on the employed blockchain technology, in this case Hyperledger Iroha[1]. Hyperledger [17] is a project that offers some industrial implementations for permissioned blockchains. Iroha is one of these implementations. Its principal difference with the rest of the Hyperledger's implementations is that it includes a service that allows working with the blockchains without needing a local copy (node). This service, called Torii, allows remote communication with an Iroha's blockchain node. For this purpose, Iroha provides a series of APIs for the main programming languages. In the proposal of this paper, these APIs are employed to create a Python connector and a REST API over it that allow the development of *Personal Health Trajectory*-aware applications and systems without the need of having local copies of the blockchains. This makes it easy to integrate the proposed solution into any kind of device, without the space or computational load limitations of having to host a blockchain node.

All components of the architecture are deployed in the information systems of the institutions and services that integrate their patients' data, except for the Python connector and its REST API. The latter must be deployed along with the healthcare application that employs them. The implementation of each of the components is discussed below and is available in public repositories (see Section VII).

Resources API. This component is responsible for storing the health information and make it referable from the blockchain. To do this, it offers a REST API where the information is sent to be stored and where it can be recovered later. When the API receives new information to store, it stores it and establishes a hash identifier and password for that information, which is returned to the sender. That identifier and key are stored in the patient's blockchain, to be employed later, when the information is retrieved. This component supports multi-model storage, so it can store any type of medical data. The format in which it return the data is the one in which it was sent.

[1]https://github.com/hyperledger/iroha

Patients' blockchains. Each patient's blockchain is implemented as an Iroha blockchain. This blockchain stores one transaction per block. This transaction represents a change in the patient's health data. If that change is to add, modify or delete information, it is determined by the description of the transaction, so a registry of changes on the patient's information is available for all the involved institutions and services. The resulting registry considering all the changes is the *Personal Health Trajectory* of a patient.

Main blockchain. This blockchain has been also implemented with Iroha. It has at least a transaction for each patient present in an institution. In the description of this transaction it is stored where the patient's blockchain is located, alongside the patient identifier. The process of adding a transaction to the main blockchain must be done by the information system managers, after deploying the patient's blockchain. If any patient changes of principal institution and, therefore, their blockchain changes location, another transaction is generated in this blockchain to store the new address of the patient's blockchain. Therefore, if there are several transactions for the same patient, the address stored in the latest one is always the one considered.

Connector. This component allows software developers to easily develop *Personal Health Trajectory*-aware applications (or health systems), using the proposed architecture as data source. The connector can be integrated into any software application, similar to a database connector. It allows users to add and retrieve information from the *Personal Health Trajectory* of a given patient. In order to use it, it is needed to connect to one of the nodes of the main blockchain or to a blockchain's node of a patient.

Connector REST API. For those developers who prefer to deploy the connector as a web service to which all their applications connect, a REST API is provided that offers the connector methods via HTTP requests.

D. Enabling development of Personal Health Trajectory-aware software

Although it has been mentioned that the proposed architecture offers a connector to develop *Personal Health Trajectory*-aware software, it has not been discussed yet which are the steps or considerations to develop this type of software. Figure 3 shows a basic diagram of the connections that any *Personal Health Trajectory*-aware application must have with the components of the proposed architecture, deployed alongside the application or in the information systems of the institutions and services that integrate their patients' data.

Personal Health Trajectory-aware applications interact with the architecture through two components.

On the one hand, an application of this type interacts with the storage system in charge of storing the evidences or records

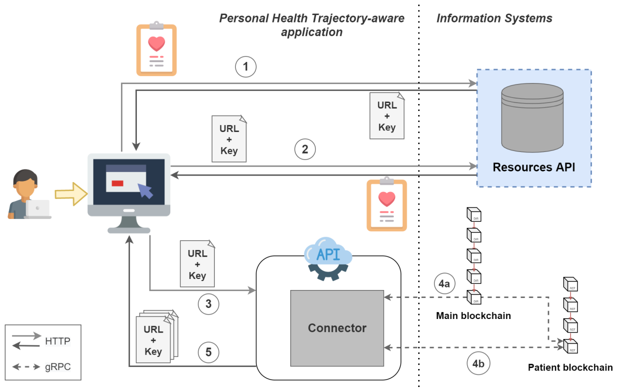


Fig. 3. Connections scheme for a Personal Health Trajectory-aware application

in the different information systems. By default the Resources APIs, if no information system has chosen a different storage method. It interacts with this component to save the records and generate a URL and key to access them (*1*) and to retrieve the records with the URL and key that identifies each one of them (*2*). The records can be retrieved from any Resources API, the URL will indicate exactly where it is stored, but the process of adding an evidence can only be performed on the Resources API of the information system to which the application has granted access. For example, in the case of a doctor's application, the records are added in the Resources API of the institution to which the doctor belongs. In this way, the records remain stored in the institution or service that generates them.

On the other hand, the application also interacts with the Connector. This interaction can be done by directly including the Connector within the application or by deploying it as a web service to be used by the application, as in Figure 3. The Connector allows storing the references generated by the interactions with the Resources API (*1*) in the blockchain of the patient to which the record belongs (*3*). The patient's identifier must be attached to this information, in case the Connector has been configured to use the main blockchain (*4a*) in order to interact with the *Personal Health Trajectory* of any patient. In this case, the Connector must have been previously configured with the address and private key of the main blockchain node with which it will operate, normally that of the information systems of the institution or service to which the application belongs. In the case of being configured to work only with the *Personal Health Trajectory* of a patient, it is not necessary to send the patient's identifier to which the record to be added belongs, but it is necessary to previously configure the Connector with the address and the private key of the patient's blockchain node with which it will operate. This way, the Connector will connect directly to this blockchain (*4b*), without going through the main blockchain.

The Connector also allows the retrieval of the set of references to records that make up the *Personal Health Trajectory* of a patient (*5*). To do this, it connects again with the patient's blockchain node, directly (*4b*) or through the main blockchain (*4a*), in the same way as explained for the process of adding new references.

If an entity develop several *Personal Health Trajectory*-aware applications or systems that interact with the architecture across the same node of the main or patient's blockchain, the more interesting option is to deploy the Connector as a web service and employ this Connector REST API with all the applications.

IV. Validation

In order to evaluate the technical suitability of the proposal —discarding social and organizational issues—, an initial validation of the proposal has been performed. For this, the proposed architecture has been deployed in the information systems of a series of simulated healthcare institutions. A web application has also been developed using Angular and Bootstrap. It uses the Connector REST API to allow doctors to operate with the *Personal Health Trajectory* of the patients of these organizations.

The developed application allows doctors from different institutions to access the data and add new evidences to patients of any of the deployed institution. In this application, the evidences stored are always documents, of any format, since this is enough to check the viability of the proposal. The results obtained with documents can be extrapolated to any type of information —stored as JSON, YAML,...—, due to the fact that information stored in blockchains —references— and the Resources APIs's web services are independent of the evidences format. The implementation of the application is also available in a public repository (see Section VII).

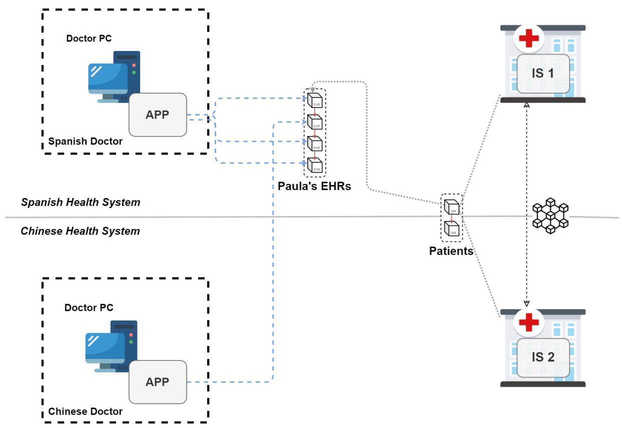


Fig. 4. Scenario where the proposal is employed to integrate information of a patient since two institutions.

The scenario —Figure 4— on which this validation is focused is the one of Paula, discussed in Section II. Therefore, the proposed architecture is used to simulate the integration of patient data from the Spanish and Chinese health systems. In this way, when Paula is treated by the Chinese health system doctor, the evidence of this intervention will be added to her *Personal Health Trajectory*. When she returns to Spain, her usual doctor can check the data from the intervention that Paula suffered in China and continue working on them.

The main hypothesis that leads to this validation is to check that the integration of the data is being done correctly and is accessible by the different institutions without patient interaction. In addition, it is checked which are the delays in the doctor's use experience due to the fact that all the mentioned architecture is behind generating the integration of the data. These delays are measured in terms of the time needed to add new data for a patient and to recover it from their *Personal Health Trajectory*.

The deployment of the architecture has been carried out in the following environment:

- **Information Systems:** Two EC2 instances from Amazon Web Services with Ubuntu 18.04 LTS, 1 virtual core at 2.5GHz and 1GB of memory.
- **Doctors computer:** a laptop with Windows 10, 16GB of RAM and an Intel Core i7-8550U processor at 1.8GHz base frequency and 4.0GHz turbo frequency. It is equipped with NVMe SSD technology for storage.

A. Results

A series of numerical and non-numerical results have been obtained from the validation of the proposal of this paper.

The first of these results has been to confirm the main hypothesis that guided this validation. Paula's health data have been correctly integrated and the doctors of both institutions have been able to work on a unique, global and complete version of her health reality.

The second part of the results includes the evaluation of the times that the architecture has taken to perform the different operations that have been carried out. The value of these times has been measured using 20 execution of the operations. The average value for each of them can be seen in Table I.

TABLE I
VALIDATION RESULTS

Time measurement	Value (s)
Locate patient's blockchain	0.079
Save evidence's resource	0.21
Add evidence to patient's blockchain	4.784
Retrieve evidence's resource	0.209
Recover evidences from patient's blockchain	0.128

From the table above, it can be seen that the most expensive operation is to add a change in the *Personal Health Trajectory* of the patient (*Add evidence to patient's blockchain*), due to the fact that a new block must be created in their blockchain for recording the change in their health information. Because the main blockchain is not altered in the process of adding changes to patient data, this cost is independent of the number of institutions and services that maintain a main blockchain node. Once a patient is added to the system, this main blockchain is only used to search where their blockchain is located. However, the number of nodes in the patient's blockchain can already influence the execution times for adding new information, due to the need of consensus between nodes. The data collected in Table I shows the execution time when there is only one node of the patient's blockchain.

As for the times to locate a patient in the main blockchain (*Locate patient's blockchain*) and to retrieve the list of changes stored in their blockchain (*Recover evidences from patient's blockchain*), it has been considered that they do not negatively impact the use experience of the doctor's application, being its values of the order of a few milliseconds. This operation is not affected by the number of nodes of the main blockchain or the patient's blockchain, because in the reading operations it is not necessary a consensus between the different nodes of a blockchain.

The times for recovering and adding files through the Resources API (*Save evidence's resource* and *Retrieve evidence's resource*) depend only on the size of the file and the bandwidth of the internet connection, so they are not discussed.

V. Discussion

After validating the proposal and commenting on the results, this section discusses if the proposal makes a really useful contribution to the world of distributed health data integration. We assume that the results obtained were those expected and that the main hypothesis of the validation has been fulfilled.

The first thing to indicate is that the main contribution of the proposed architecture is not the use of a blockchain to store references to all the health data of a patient. This is already done by other proposals, where the suitability of this technology is already sufficiently proven. On the opposite, it should be considered that the main contribution that this proposal makes to this area of research is the use of the blockchains' federation to promote easier access to integrated patient information by the institutions and to keep alive the structure that holds the data of each patient integrated. In this sense, this proposal has solved the problems discussed in the introduction —without renouncing the benefits already offered by current proposals— by which the use of blockchain as a method to develop patient-centered health systems still generates some doubts. The institutions and services will continue to keep the data they generate in their systems, but now they have a structure that allows them to operate with a global vision of patient health, and not with the fragmented visions with which they operated until now. This is a benefit both for them and for the patients.

In addition, the proposal facilitates the transition to patient-centered health systems by offering a Connector that simplifies the development of health applications and systems that consume the *Personal Health Trajectory* data of patients. Thanks to this Connector and a well-defined procedure for the development of *Personal Health Trajectory*-aware applications, the proposed architecture is really useful for health software developers. In this way, it encourages health software developers to start using this proposal as data source for their developments.

Furthermore, with the proposal presented in this paper, the suitability of blockchain to develop patient-centered health systems has only been reaffirmed. In the first place, and as already indicated in previous works, blockchain has shown itself to be adequate due to its qualities of decentralization, sharing and openness guaranteeing traceability and security in the data as well. All this obtained by means of the ledger abstraction which model the shared unique record of the transactions between different systems. In second place, because the different advantages that have been indicated throughout the proposal and that have been possible thanks to blockchain. For example, federating the different patients' blockchains with another blockchain allows all institutions and services to be aware of the changes in patients' blockchain locations at the same time and to work with the same blockchain for one patient. The fact that the structure that maintains the *Personal Health Trajectory* of a patient is another blockchain, empowers the patient with their data, allowing them to have a node of it on their devices and ensuring that no one malicious can generate changes in their data. Therefore, with all this, the suitability of blockchain for this proposal is more than clear.

In any case, the proposal of this paper is not free of debate either. The proposed architecture has tried to be as less intrusive as possible for the institutions and services, providing Resources APIs and Connector, even allowing them to maintain their storage system if it allows referencing the information from the blockchain. However, institutions and services, even if they do not replace their information systems, need to include a series of components in them.

VI. Future works and conclusions

The proposal of this paper offers a method to build patient-centered health systems, by integrating patient data, which is distributed among the different institutions and services that generate it, in a unique and global vision: its *Personal Health Trajectory*. Thus, institutions and the patients themselves can operate on a complete version of patients' health information.

To do this, the concept of blockchains' federation is defined and applied in a proposed architecture. This architecture defines a series of components that software developers can use to create applications or systems that consume the architecture's data. These types of applications —*Personal Health Trajectory*-aware applications— and the procedure for connecting them to the proposed architecture has been defined.

As future steps in the proposal, a more complex validation of the architecture is expected, with better performance measures, scalability tests —with more blocks and more nodes, both for patients and main blockchain—, stress tests and formal comparison with other type of solutions, like a traditional database or single blockchain proposals.

VII. Data Availability

The software developed is available in Zenodo:

- **IS components**: 10.5281/zenodo.4588545
- **Connector (and its API)**: 10.5281/zenodo.4588534
- **Doctor app**: 10.5281/zenodo.4588555

Acknowledgment

This work was supported by the project 0499_4IE_PLUS_4_E funded by the Interreg V-A España-Portugal 2014-2020 program, by the project RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

[1] D. Kalra, "Electronic health record standards," 2006.

[2] A. Gatouillat, Y. Badr, B. Massot, and E. Sejdic, "Internet of Medical Things: A Review of Recent Contributions Dealing with Cyber-Physical Systems in Medicine," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3810–3822, oct 2018.

[3] J. Rojo, D. Flores-Martin, J. Garcia-Alonso, J. M. Murillo, and J. Berrocal, "Automating the interactions among iot devices using neural networks," in *2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE, 2020, pp. 1–6.

[4] A. Roehrs, C. André Da Costa, R. Da, R. Righi, Kleinner, and S. Farias De Oliveira, "Personal Health Records: A Systematic Literature Review," *Journal of Medical Internet Research*, vol. 19, no. 1, p. e13, 2017. [Online]. Available: http://www.jmir.org/2017/1/e13/

[5] N. Mäkitalo, D. Flores-Martin, J. Berrocal, J. García-Alonso, P. Ihantola, A. Ometov, J. M. Murillo, and T. Mikkonen, "The internet of bodies needs a human data model," *IEEE Internet Computing*, vol. 24, no. 5, pp. 28–37, 2020.

[6] J. Rojo, J. Hernandez, and J. M. Murillo, "A personal health trajectory api: Addressing problems in health institution-oriented systems," in *Web Engineering*, M. Bielikova, T. Mikkonen, and C. Pautasso, Eds. Cham: Springer International Publishing, 2020, pp. 519–524.

[7] S. J. Henly, J. F. Wyman, and J. E. Gaugler, "Health trajectory research: A call to action for nursing science," *Nursing Research*, vol. 60, no. 3 SUPPL., may 2011.

[8] T. Spil and R. Klein, "Personal health records success; why google health failed and what does that mean for Microsoft HealthVault?" in *Proceedings of the Annual Hawaii International Conference on System Sciences*. IEEE Computer Society, 2014, pp. 2818–2827.

[9] M. Kyazze, J. Wesson, and K. Naude, "The design and implementation of a ubiquitous personal health record system for south africa," *Studies in health technology and informatics*, vol. 206, p. 29, 2014.

[10] B. Prados-Suárez, C. Molina Fernández, and C. P. Yañez, "Electronic Health Records Aggregators (EHRagg)," *Methods of Information in Medicine*, vol. 59, no. 02/03, pp. 096–103, may 2020.

[11] Y. Zhang, M. Qiu, C.-W. Tsai, M. Hassan, and A. Alamri, "Health-cps: Healthcare cyber-physical system assisted by cloud and big data," *IEEE Systems Journal*, vol. 11, pp. 1–8, 08 2015.

[12] A. Roehrs, C. A. da Costa, and R. da Rosa Righi, "OmniPHR: A distributed architecture model to integrate personal health records," *Journal of Biomedical Informatics*, vol. 71, pp. 70–81, jul 2017.

[13] S. L. Cichosz, M. N. Stausholm, T. Kronborg, P. Vestergaard, and O. Hejlesen, "How to Use Blockchain for Diabetes Health Care Data and Access Management: An Operational Concept," *Journal of Diabetes Science and Technology*, vol. 13, no. 2, pp. 248–253, mar 2019. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/30047789/

[14] K. Fan, S. Wang, Y. Ren, H. Li, and Y. Yang, "MedBlock: Efficient and Secure Medical Data Sharing Via Blockchain," *Journal of Medical Systems*, vol. 42, no. 8, pp. 1–11, aug 2018. [Online]. Available: https://doi.org/10.1007/s10916-018-0993-7

[15] M. Kassab, J. Defranco, T. Malas, V. V. Graciano Neto, and G. Destefanis, "Blockchain: A panacea for electronic health records?" in *Proceedings - 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare, SEH 2019*. Institute of Electrical and Electronics Engineers Inc., may 2019, pp. 21–24.

[16] L. Kan, Y. Wei, A. Hafiz Muhammad, W. Siyuan, L. C. Gao, and H. Kai, "A multiple blockchains architecture on inter-blockchain communication," in *2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C)*, 2018, pp. 139–145.

[17] V. Dhillon, D. Metcalf, and M. Hooper, *The Hyperledger Project*. Berkeley, CA: Apress, 2017, pp. 139–149.

Appendix F

Trials and Tribulations of Developing Hybrid Quantum-Classical Microservices Systems

Authors: *Javier Rojo, Enrique Moguel, David Valencia, Javier Berrocal, Jose García-Alonso and Juan M. Murillo.*

Publication type: *International workshop paper.*

Workshop: *2nd Quantum Software Engineering and Technology Workshop - Collocated with the IEEE International Conference on Quantum Computing and Engineering (QCE21).*

Year of publication: *2021.*

CEUR: *Vol-3008/paper2.pdf*

Trials and Tribulations of Developing Hybrid Quantum-Classical Microservices Systems

Javier Rojo, Enrique Moguel*, David Valencia, Javier Berrocal, Jose García-Alonso* and Juan M. Murillo

SPILab - Social and Pervasive Innovation Lab. Quercus Software Engineering Group. Escuela Politécnica. Avenida de la Universidad s/n. University of Extremadura. 10004 - Cáceres. Spain
** Corresponding Author: enrique@unex.es / jgaralo@unex.es*

Abstract
Quantum computing holds great promise to solve problems where classical computers cannot reach. To the point where it already arouses the interest of both scientific and industrial communities. Thus, it is expected that hybrid systems will start to appear where quantum software interacts with classical systems. Such coexistence can be fostered by service computing. Unfortunately, how quantum code can be offered as a service still misses out on many of the potential benefits of service computing. This paper takes the traveling salesman problem and tackles the challenge of giving it an implementation in the form of a quantum microservice. Then it is used to detect which of the benefits of service computing are lost in the process. The conclusions help to measure the distance between the current state of technology and the state that would be desirable to have a real quantum service engineering.

1. Introduction

Quantum computing has been a relevant research field for more than 20 years, bringing together classical information theory, computer science, and quantum physics [1]. More recently, the development of quantum computers has brought us to the Noisy Intermediate-Scale Quantum (NISQ) era [2], where quantum computers with more than 50 qubits, although limited by the noise in quantum gates, are starting to perform tasks that may surpass the capabilities of classic computers.

Alongside this scientific development, quantum computing is also experiencing a significant commercial growth [3]. Several major computing corporations have built their own quantum computers and are offering them to users, mostly in a pay-per-use model. Engineers have designed and implemented dozens of quantum programming languages, simulators, and toolkits. All of this is paving the way for the development of quantum software and services.

Nevertheless, for the time being, classical and quantum services must not only coexist but interact with each other [4]. This coexistence has been called by some researchers hybrid

2nd Quantum Software Engineering and Technology Workshop, co-located with IEEE International Conference on Quantum Computing and Engineering (QCE21) (IEEE Quantum Week 2021), October 18–22, Virtual Conference
javirojo@unex.es (J. Rojo); enrique@unex.es (E. Moguel*); davaleco@unex.es (D. Valencia); jberolm@unex.es (J. Berrocal); jgaralo@unex.es (J. García-Alonso*); juanmamu@unex.es (J. M. Murillo)
0000-0001-9189-1133 (J. Rojo); 0000-0002-4096-1282 (E. Moguel*); 0000-0001-5571-2142 (D. Valencia); 0000-0002-1007-2134 (J. Berrocal); 0000-0002-6819-0299 (J. García-Alonso*); 0000-0003-4961-4030 (J. M. Murillo)

classical-quantum systems [5, 6]. A natural way to approach such collaborative coexistence is by following the principles of service engineering and service computing.

Already, companies and researchers are leaning towards the use of quantum infrastructure and quantum software as a service, as they are used to do with classical computing resources. Offerings like IBM Quantum Computing[1] or Amazon Braket[2] allow them to use the still very expensive to own and operate quantum computers with moderated costs. This model also fits very well with the needs of hybrid systems where both classical and quantum software will be executed on hardware on the cloud regardless of the type of computer needed.

Such deployment architectures are also perfectly aligned with the microservices architectural pattern [7]. Following this architecture, a complex system is conceived as a set of distributed microservices, where each microservice is a cohesive, independent process that interacts with the rest of the system through messages. Bringing microservices to hybrid systems, we have solutions where both classical and quantum services coexist to solve complex problems.

To achieve these hybrid microservices architectures, the first step is to convert a quantum piece of software into a microservice. Conceptually, there is no difference between a classical and a quantum microservice, an independent process that can interact with the rest of the system through messages. Furthermore, from a service engineering point of view the specific hardware in which a microservice is executed, classical or quantum, should be irrelevant. However, the current state of quantum services is very different from classical services and requires specific approaches to create working hybrid microservices architectures.

Running a quantum algorithm as a microservice is possible. The quantum algorithm can be wrapped by a classical service and integrated into the complex architecture. However, the current technological state of the available quantum platforms imposes some limitations. First, they make quantum services invocation and execution to be closely coupled with the quantum processor in which they will be executed. Also, the different quantum computers provide the results of the executed process in different ways thus making even stronger coupling. In addition, due to the existing noise in quantum computers, results are subject to errors and these errors are also usually dependent on each specific quantum computer and qbit topology. This increases, again, the coupling between service and hardware. Finally, due to the quantum system collapse, is not always possible to obtain intermediate verification of results which drastically reduces services orchestration possibilities.

For all these reasons, invoking a quantum microservice in an agnostic way is not possible and violates all the principles of software engineering. These limitations mean that most of the advantages of service-oriented computing are lost when involving quantum microservices. Especially, those related to the different software quality x-abilities like composability, maintainability, reusability, modularity, etc. To address this situation, techniques of classical service engineering should be brought to the domain of quantum service engineering [8].

Specifically, in this paper, we focus on the technical aspects needed to create a quantum microservice. To illustrate the current state of technology, we have developed a quantum microservice to solve the well-known Traveling Salesman Problem (TSP). We use the Amazon Braket platform to deploy it and to analyze its characteristics in the different quantum hardware

[1]https://www.ibm.com/quantum-computing/
[2]https://aws.amazon.com/braket/

supported by Amazon. Although a specific algorithm (TSP) and platform (Amazon Braket) are used, we believe that the problems and limitations found are directly transferable to other quantum algorithms and platforms. From the results obtained from executing this microservice, we discuss the current limitations of hybrid microservices architectures and detect which of the benefits of service computing are lost in the process.

In order to do that, the rest of the paper is organized as follows. Section 2 present the background of this work. Section 3 details the traveling salesman problem used as the case study for this work, paying special attention to the quantum implementations of this well-known problem. Section 4 presents how to offer a quantum algorithm as a microservice using the Amazon Braket platform. Section 5 lists the main results obtained by executing the quantum microservices in the different hardware and discusses the current limitations of quantum microservices. And finally, Section 6 presents the paper conclusion and future works.

2. Background

Microservices in particular, or Service-Oriented Architecture in general, is a software engineering approach focused on the use of services as the fundamental element to develop software solutions [9]. Although different definitions and proposals can be found in the literature, there are some aspects of microservices that are mostly agreed upon.

First, a microservice can be defined as a single-responsibility entity that encapsulates data and logic. They are exposed remotely and can be deployed, changed, substituted, and scaled independently of each other [9].

When developing microservices solutions, different computing paradigms and storage paradigms can be used [10]. Different programming languages are used, including a mix of functional and imperative ones, and databases, including relational and NoSQL ones, to provide solutions to complex problems.

There is no standard communication mechanism for microservices. Nevertheless, in practice, REST HTTP and asynchronous message queues are the most commonly used ways to expose microservices [11].

Similarly, although there is no constraint on where and how microservices should be deployed, in practice most solutions are developed with a strong orientation towards the cloud [12]. The elasticity and distribution provided by the cloud are features well aligned with the microservices approach.

Finally, although they are completely independent paradigms that are not exclusively related to microservices, continuous delivery and DevOps approaches are usually applied during the development of microservices systems [13].

Having all this into account, we can assume that microservices will be a good fit for a hybrid classical-quantum solution. In this regard, some of the most recent works on quantum software development are helping to align both worlds. Especially, from a cloud computing perspective.

Currently, most commercial quantum computers are accessible through the cloud, similar to the classical Infrastructure as a Service model. Some researchers have called this access Quantum Computing as a Service (QCaaS) [14]. Through QCaas developers can use some of the existing quantum computers to execute their own code. However, this access is still very dependant of the specific hardware, requiring developers to have a deep understanding of it.

To address some of the QCaaS limitations and increase its abstraction level to create more complex quantum software, multiple research and commercial efforts are underway. In the academic world, quantum software engineering is starting to emerge, attracting the attention of researchers [15, 16]. This discipline seeks to bring the knowledge and expertise of classical software engineering to the domain of quantum software development. Specifically, some works are starting to pay attention to aspects of quantum development more closely related to microservices. For example, in [17] the authors propose the term Quantum application as a Service (QaaS) to narrow the gap between classical service engineering and quantum software. Also, [18] proposes an extension to TOSCA, a standard for software deployment on the cloud, to allow the deployment of quantum services.

From a different point of view, , quantum computers with practical utility and hybrid classical-quantum algorithms are emerging, such as Quantum Approximate Optimization Algorithm (QAOA) |[19, 20] or Variational-Quantum-Eigensolver (VQE) [21, 22].

In addition, companies are also trying to create more complex quantum solutions. Amazon, one of the global leaders in the cloud and computing services domains, has created the Amazon Braket platform that provides a development environment for quantum software engineers. At the moment of writing this article, Braket supports hardware from three different vendors (D-Wave, IonQ, and Rigetti). D-Wave machines fall in the category of adiabatic quantum computers, while IonQ and Rigetti machines can be classified as circuit-based quantum computing. Having these two different computational models available increases the tools at the disposal of quantum software developers, but also increase the complexity of programming quantum services. To use adiabatic-based machines developers must reformulate the problem they want to solve as a quantum annealing metaheuristic specification [23]. To use circuit-based machines developers should know the details of quantum gates and how to adapt the problem they want to solve to a quantum circuit [24]. This makes it more complicated for developers to create independent, maintainable, agnostic quantum microservices.

Other companies are creating similar platforms, like the above-mentioned IBM Quantum or like QPath[3]. However, as far as the authors know, there is no proposal that has addressed the problems and limitations of creating quantum microservices for the development of hybrid solutions.

3. Traveling Salesman Problem

To illustrate the technical limitations of current quantum platforms for the development of quantum microservices we have chosen a very well-known and studied problem. The traveling salesman problem is a famous example in the class of NP-Class problems [25]. It can be categorized as an optimization problem, in which the traveling salesman must visit all cities inside a route, minimizing the traveled distance. Thus, in the classical definition of the problem there exist cities, usually described as nodes, roads connecting those cities, that can be considered as links between these nodes each with a weight indicating the distance. The main drawback of these kinds of problems lies in the increasing of possible solutions with the increase of the

[3]https://www.quantumpath.es/

problem size, i.e. with 5 cities there exist 12 possible routes whereas for 25 cities the number of routes grows to 3.1×10^{23}.

Solving this problem by classical computing methods it is not always optimal. These methods have been developed for years as replacements to brute force solutions on these optimization problems, but still have certain limitations. In recent years, due to the expansion of quantum computing, researchers have begun to develop quantum algorithms that solve these problems: both for the perspective of adiabatic quantum computing [26] and for the perspective of gate-based quantum computing [27, 28].

3.1. Formulation of the TSP problem

To formulate the problem we have followed the previous works [29, 30]:

Definition 1. *Let $G = (N, A)$ be a directed graph, where $N = \{0, 1, ..., n\}$ is the finite set of nodes, also known as cities, and $A = N \times N$ is the set of roads or arcs connecting the cities. For every pair (u, v) of cities there exists a road in A. A tour is defined by the order in which the cities are visited.*

Definition 2. *Let city 0 denote the depot and assume that every tour begins and ends at the depot. Each of the remaining n cities appears exactly once in the tour. We denote a tour as an ordered list $P = (p_0, p_1, ..., p_n, p_{n+1})$, where p_i is the index of the city in the i-th position of the tour. According to our previous assumption $p_0 = p_{n+1} = 0$, which can also be indicated as $p_i(mod(n+1))$.*

Definition 3. *For every pair (u, v) of cities $u, v \in N$, there is a cost $c_{u,v}$, for traversing the road (u, v). This cost of traversing the road from u to v generally consists of the travel time from city u to city v.*

Based on the previous definitions, the objective function is to minimize the sum of the arc traversal costs along the tour, and can be summarized as:

$$min \sum_{i=1}^{n+1} c_{p-1,p} \tag{1}$$

In eq. (1), it is assumed that $(p_0, p_1, ..., p_n, p_{n+1})$ is a feasible tour.

3.2. TSP on Quantum Computing Architectures

The classical formulation of the problem is proposed as an optimization, making it extremely suitable and straightforward for adiabatic quantum computers. More challenging is the proposal of solutions tailored for quantum computers based on quantum circuits and gates. In this subsection, a solution for the TSP on each type of quantum computers is described.

3.2.1. TSP on Adiabatic Quantum Computing

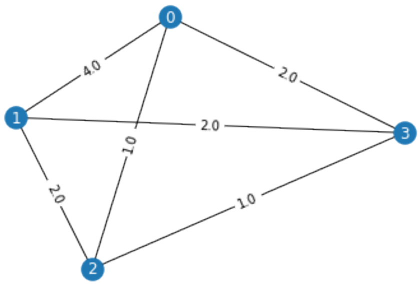
For this type of quantum computer, Amazon Braket provides a proposal of a solution based on quantum annealing. This proposal employs the Lagrange multipliers and Quadratic Unconstrained Binary Optimization (QUBO) problem matrix [31] where the graph of the problem is encoded such that the evolution of the system through quantum annealing offers the minimum energy cost, that is to say, the minimum travel cost.

To do this, the graph is internally converted to the form of an Ising model or Quadratic Unconstrained Binary Optimization Problem (QUBO), and later on, quantum annealing is applied.

As input for the algorithm, it is necessary to provide a matrix with the costs of traveling between cities. An example of this matrix is showed in Figure 1-(a). From it, a graph like the one on Figure 1-(b) can be generated.

	0	**1**	**2**	**3**
0	0.0	4.0	1.0	2.0
1	4.0	0.0	2.0	2.0
2	1.0	2.0	0.0	1.0
3	2.0	2.0	1.0	0.0

(a) Input costs' matrix.



(b) Generated cities graph.

Figure 1: Input for the annealing-based solution of the TSP.

As output, the Hamiltonian cycle with the lowest cost is returned [32] with 2 considerations: including revisiting the starting point or not revisiting it, i.e., in Figure 2 it is provided a graphic representation of the path with less cost, without returning to initial point.

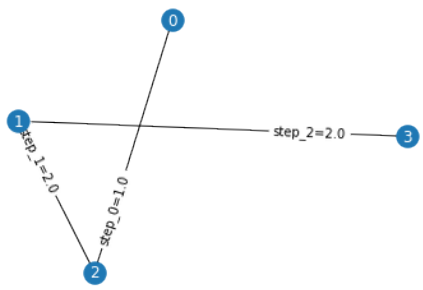


Figure 2: Output of the annealing-based solution of the TSP

3.2.2. TSP on Gate-based Quantum Computing

Solving the TSP in quantum machines programmed via quantum gate-based circuits is much more complicated. Optimization problems, such as TSP, can be addressed simply in adiabatic quantum computers by their nature, but to work on gate-based quantum machines a workaround is needed. This is related to the complexity of defining a circuit that allows finding the solution to the problem in any situation, obtaining in many cases circuits that only solve the problem for a specific case.

There are different approaches in the literature to solve the TSP in gate-based quantum computers, by means of the application of different quantum algorithms and solutions. In this work, the circuit proposed by [28] will be used. It is based on the Quantum Phase Estimator (QPE) algorithm, which calculates a phase for each of the eigenstates considered. These eigenstates correspond to each of the possible Hamiltonian cycles solutions of the problem. Having obtained the phase of each eigenstate, they are later checked to select the lowest using other quantum algorithms such as the minimum finding [33]. Thus, the optimal path is the one for which the QPE obtains a minimum phase. This quantum algorithm has been implemented in Amazon Braket.

As opposed to the quantum annealing solution, the circuit obtained is not generic, one circuit must be generated for each eigenstate and an implemented circuit is associated with a concrete graph due to the nature of the controlled-U gates and the Unitary matrices obtained. The included code fragment is tailored for the graph shown in Figure 1. This way, subsequent experiments, and the obtained results will be easier to compare. Nonetheless, one must have in mind that if any of the elements of the graph change, the circuit should be changed as well.

After obtaining the result of the quantum part of the algorithm, classical computations must be applied to determine which eigenstate has as result the phase of smaller value and, knowing which is that eigenstate, return the associated Hamiltonian cycle.

Analyzing both solutions to the TSP, it is clear that the main complication lies in the case of quantum gate-based machines. Making generic circuits, which enable to take as input a series of parameters that condition them —in this case, a circuit for the QPE algorithm that works with any graph—, is something that has already been studied in proposals like [27, 34] that use Parameterized Quantum Circuits. Specifically, Matsuo et al. [27] propose a circuit to solve the TSP for any input graph in gate-based quantum machines, using the VQE algorithm. In this work solutions of this type have not been used since it has not been considered essential for the performed experiments. Being able to solve a given TSP is enough to build a microservice and analyze it.

4. Quantum microservices

From the two solutions to the TSP discussed in the previous section, a microservice with two endpoints has been implemented as shown in Figure 3. The implementation of this microservice and the notebooks with the implementations of the TSP in adiabatic and gate-based quantum computing are available in the following repository[4].

The two endpoints allow other microservices of the system to invoke the solution of the TSP problem, one using the gate-based solution and the other the adiabatic solution. Both endpoints are implemented in Python, using Flask[5]. This endpoint is in charge of deploying and executing the corresponding quantum algorithm.

These algorithms are executed on Amazon Braket and, therefore, different quantum computers can be chosen. In the case of the algorithm for adiabatic quantum computing, Braket supports the execution on the quantum computers *D-Wave 2000Q* and *D-Wave Advantage_system*. In the case of gate-based quantum computing, it can be executed on the simulators *LocalSimulator*, *TN1*, and *SV1* or on the quantum computers *IonQ*, *Rigetti Aspen-8*, and *Rigetti Aspen-9*. In any

[4]https://github.com/frojomar/ICWS2021-quantum-classical-microservices
[5]https://flask.palletsprojects.com/en/1.1.x/

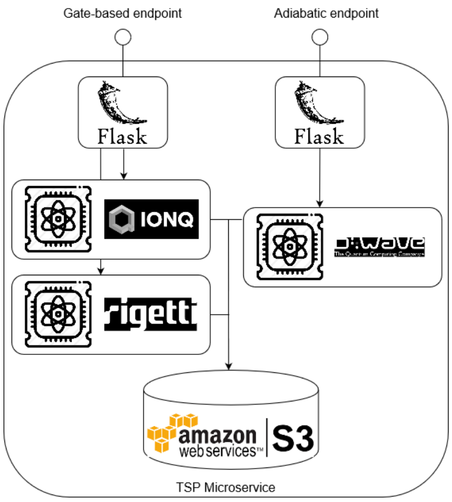


Figure 3: Deployment architecture of the TSP hybrid microservice

case, the result of the execution of the quantum algorithms is always stored in an Amazon S3 storage (except in the case of *LocalSimulator*).

In order to choose over which hardware the microservice's quantum part is going to be executed, both endpoints employ a parameter. This parameter is codified as a *query param* called *device*. Taking into account the number of QPUs and simulators available, the query param *device* must take one of the following values:

- Adiabatic quantum computing endpoint: *dwave_dw2000*, and *dwave_advantage*.
- Gate-based quantum computing endpoint: *local*, *tn1*, *sv1*, *ionq*, *riggeti_aspen8*, and *riggeti_aspen9*.

Next, implementation details of both endpoints will be provided showing that, despite the fact that each one of them belongs to a different type of quantum computing, the way of enclosing the quantum code with a classical computing wrapper, that allows its execution as a microservice, does not differ.

4.1. Adiabatic quantum computing endpoint

Figure 4 shows the code for the endpoint of the adiabatic solution.

As input, the endpoint needs a .txt file with the weights of the matrix, in addition to the query param *device*. As a result, a JSON object is returned including the best route found for the TSP problem and the distance to cover the route.

4.2. Gate-based quantum computing endpoint

As in the previous endpoint, Figure 5 shows the code for the endpoint of the circuit-based solution.

```python
@app.route('/execute/adiabatic', methods=["get"])
def execute_adiabatic_quantum_tsp():
    machine = request.args.get('device')

    if machine not in adiabatic_machines_arn:
        return "Not machine", 400

    if 'file' not in request.files:
        return "Not file", 400
    file = request.files['file']
    if file.filename == '':
        return "Not file", 400

    filename = "graph.txt"
    file.save(filename)

    data, G, weights = def_graph(filename)

    best_route, best_distance = TSP(data, G, weights,
                                    s3_folder,
                                    adiabatic_machines_arn[machine])

    response = {
        "best_route":best_route,
        "best_distance":best_distance
    }
    return jsonify(response)
```

Figure 4: Adiabatic quantum computing endpoint code

```python
@app.route('/execute/gate', methods=["get"])
def execute_gate_based_quantum_tsp():

    machine = request.args.get('device')

    if machine not in gate_machines_arn:
        return "Not machine", 400

    eigenstates = ["11000110", "10001101", "11100001"]
    results = {}
    for e in eigenstates:
        counts = QPE(e, s3_folder, gate_machines_arn[machine])
        measure = list(counts.keys())[0]
        eigenstate = measure[n_ancilla:]
        phase = measure[:n_ancilla]
        results[eigenstate] = phase

    hamiltonian_cycle = get_minor_route_by_phase(results)

    response = {
        "best_route":hamiltonian_cycle
    }
    return jsonify(response)
```

Figure 5: Gate-based quantum computing endpoint code.

Depending on whether the TSP is to be executed on a real quantum computer or on a simulator, the way in which the quantum code is executed changes. Therefore the selected machine is given as a parameter to the method that makes the quantum call. When the endpoint is run outside of a local simulator the result is stored in s3 storage, from where it is retrieved. In particular, if it is run on a quantum computer, the results are always stored in an s3 and, in addition, they take some undefined time to be available.

When running the code on a quantum computer, a task with an identifier is created. With this identifier, developers can check the status of the task, which will change from CREATED, QUEUED, and RUNNING until it reaches COMPLETED; or CANCELLED or FAILED if something goes wrong. At this point, the result can be recovered. In any case, it is necessary to define a poll timeout to prevent the execution from being blocked.

All this is done transparently to the system since, when the microservice is invoked, it is checked with which device the code is to be executed and, if it is a real quantum computer, the wait is done internally in the call to the endpoint.

In order to execute this endpoint, it is necessary to send the query param *device* with the device where the quantum algorithm is to be executed. In this case, the quantum circuit is not parameterized, so it does not allow the execution on different networks. That same graph will be always used as mentioned above. As output, this endpoint returns the optimal path but not the path cost, as the algorithm does not know the weight of each path.

5. Quantum-Classical Hybrid Microservices System Trial Evaluation

After developing the described microservice, different metrics were used to evaluate its performance and the limitations of including a quantum microservice in a hybrid system.

To proceed with the evaluation, several HTTP requests were made from the API client tool Postman[6], which allows performing petitions to REST APIs and take metrics such as response time, response size, etc.

The developed microservice was locally deployed during the evaluation. More specifically, it was deployed on a laptop running Windows 10 with 16 GB of RAM and an Intel Core i7-8550U processor at 1.8 GHz base frequency and 4.0 GHz turbo frequency, equipped with NVMe SSD technology for storage.

Taking advantage of the fact that the adiabatic solution implemented for the TSP is generic and the endpoint allows giving a graph as input, the evaluation for both adiabatic and gate-based implementations has been carried out using the same graphs as input. Thus, the comparison between the results obtained with both computation models is comparable.

Table 1 summarizes the launched executions and the corresponding results obtained. The first 2 lines correspond to the Adiabatic Quantum Endpoint and the rest of the table is related to the Gate-based Quantum Endpoint.

Number of qubits. One of the main limitations of current quantum computers lies in the number of qubits available, especially in the case of gate-based systems, and this directly affects the ability to run the microservice or limits its execution. Table 2 shows the results from considering the TSP described in Figure 1. As one can see, in the case of Gate-based circuits the number of qubits amounts to 14 (8 for eigenstates + 6 for phase). In the case of the quantum annealing solution, the number of qubits necessary is unknown, since the Braket provided implementation was used. Nevertheless, both D-wave machines available at Braket had enough qbits to run the algorithm. In any case, even for such a simple problem (3 possible routes considering the links between 2 nodes as symmetric non-directed), it exceeds the number of qubits available (11 qubits) to be executed on the IonQ hardware and it is not possible to execute on this architecture. In the case of the Rigetti hardware, it provides enough qubits.

[6]https://www.postman.com/product/api-client/

Architecture	# of shots	Result obtained
DWAVE 2000Q6	$10^2, 10^3, 10^4$	[0,3,1,2] (Consistent)
DWAVE ADVANTAGE	$10^2, 10^3, 10^4$	[0,3,1,2] (Consistent)
LocalSimulator	$10^3, 10^4, , 10^5$	[0,3,1,2], [0,1,2,3]
TN1	—	Error
SV1	$10^3, 10^4$	[0,1,2,3] (Inconsistent)
IonQ	—	Error
Aspen 8	—	Error
Aspen 9	10^3	Error

Table 1
Executions on each endpoint and shots conducted.

Version	# of Qubits	# of Classical bits
Gate-based TSP	14 (eigenstates+ phase)	6 (collapsing phase)
Dwave's solution	Unknown	Unknown

Table 2
Executions conducted and number of qubits and classical bits

In the case of quantum services, this not only shows the limited power of the current hardware but also the need that quantum service engineering will have for mechanisms to determine the number of qubits the execution of service will need. Due to the nature of quantum algorithms for the different architectures, there is no trivial way to obtain this number. This will be a key question in developing quantum services execution planners with implications in several other aspects of the service like if the cost of only the hardware with more qubits can be used or response time if the waiting time for that hardware is longer.

Number of shots. Due to the problems that arise due to the characteristics of actual quantum computers, mainly noise in the qubits state, the experiments must be conducted several times or ”shots” to be statistically consistent.

For a real quantum service technology, the responsibility of performing the different executions to get a consistent result cannot be delegated to the client nor the customer who only wants to use technology to get a correct result, at least within a given margin of error, and with an economic cost known in advance. How the number of shots required is estimated will have a direct impact on the cost of the service executions. This reveals some issues, related to service quality and costs, that still have to be addressed by quantum services engineering.

Precision of results. Table 1 shows the discrepancies in the results achieved. In the first rows, the results obtained by DWave's machines are shown. Both show consistent results given the number of shots considered. For the rest of the platforms, different problems have arisen. First, in some of the architectures, it has been impossible to execute the code, more specifically it happened in TN1, IonQ, and Rigetti 8. On IonQ the number of qubits available was insufficient to run the service. On Apen 8, the service was unavailable at the time of running the experiments. Finally, in Aspen 9, although the code was sent for execution, it was in the state QUEUED for more than 3 hours, not having executed any of the 1000 shots. In contrast, in the case of SV1, the code was sent and executed. However, the results obtained were different in different executions. Most of the time the result was [0,1,2,3] which does not correspond to the optimal solution. Similar results were observed when working with the simulated architecture, where the number of shots must be higher than 100 to obtain the correct solution with acceptable statistical certainty.

Again, in a real scenario, the responsibility of determining the number of shots and the precision of the results cannot be delegated to the client service nor the customer. The customer pays for a service that is expected to provide correct results, within an agreed level. This points out the need for some kind of logic in service execution planners to determine the number of shots needed to provide a correct solution. It should also be noted that predictions can affect the planning, availability, and accuracy of the platforms' results and all of this will impact the service qualities that will have been previously negotiated with the customers. These are therefore issues that, while affecting the technical aspects of future quantum services platforms, will also affect their financial profitability.

Response times. Other evaluated parameter was response time. The measure corresponds to the time elapsed between sending the request and receiving the result. This time has been measured for all the machines where the code has been correctly executed. Specifically, the SV1 and LocalSimulator gate-based simulators, and the D-wave 2000_Q6 and D-wave Advantage adiabatic quantum machines. For the first ones, the difference is significant. In the LocalSimulator, the execution took about 3 seconds with 1000 and 10000 shots, and about 7 seconds with 100000 shots. However, in SV1 it took an average of 27 seconds, with a margin of up to 10 seconds between the fastest and slowest runs. In the case of adiabatic machines, the result is similar for both. In the case of D-wave 2000_Q6, the runs exceed 20 seconds, and in the case of D-wave Advantage 25 seconds.

From this, it can be concluded that the highest cost in terms of time is incurred when sending the quantum code to execution. Possibly, due to the waiting times in the queue. Nevertheless, these results give the user a feeling of unreliability when using the platforms which, in real service engineering, must be avoided. Dealing with this will again require quantum service platform planners to count on reliable resources and estimates. This highlights how far current quantum service platforms are from reaching to be acceptable to potential customers of a quantum services platform.

Economic cost. Lastly, the economic cost of invoking each solution has been considered. At the moment, Amazon Braket establishes a fixed price per quantum task executed, which is the same for all the supported hardware. Moreover, an additional cost is paid for each shot and this cost is different for the different hardware. These costs, while predictable if the hardware to be used and the number of shots to be executed are known, are far from what is needed to agnostically implement microservices on hybrid quantum-classic systems. Especially due to the uncertainty that arises from the unavailability of services, response time, uptime, state of the quantum system, and so on, parameters are extremely important to be able to assure the quality and SLAs inherent in services.

Furthermore, from the evaluation performed, some other more abstract questions arise as well. First and foremost, there is a need for abstractions to define quantum problems in a more general way. This abstraction could be used as a starting point that can be specialized in terms of quantum annealing, gate-based circuits, or whatever future technology or new programming paradigm appears for quantum computing. An initial solution, for the specific case presented in this paper, could be to develop a single generic endpoint in charge of unifying the adiabatic and gate-based solutions. Such an endpoint will have the responsibility of adopting an abstract representation of the TSP problem to the needs of the specific quantum hardware in which it will be executed. Even then, the solution will still depend on the service platform, Braket in this case. This remarks one unresolved question in quantum service engineering. When a service is invoked, the invoker only cares for the response. The service platform should address the execution of different architectures and the problem formulation for each of them if there is a benefit in doing so. Delegating these responsibilities to the client makes it more tightly coupled with the microservice and reduces the benefits provided by service engineering.

To summarizing, given the above-mentioned problems, current quantum services platforms pose the following inconveniences for the development of quantum microservices. First, services are tightly coupled with the quantum code to be executed. Moreover, services are also tightly coupled with the hardware in which the quantum code will be executed. Additionally, platforms do not allow a service implementation to be transparently replaced by another, as can happen in traditional services as long as the API is maintained. Also, quantum platforms are not able to decide, on execution time, where and how a service will be executed to optimize answering petitions based on performance aspects of the different supported hardware. Finally, all the experiments developed in this paper involve only a single service which is completely unreal. The most simple example of a real microservices-based system would involve several ones. However, there is also an absolute lack of mechanisms for quantum services orchestration. All of these limitations have a significant impact on some of the most relevant aspects of quality services, like composability, maintainability, reusability, or modularity of quantum services limiting the current potential of these services. These limitations affect not only researchers or developers but also the platforms that provide access to quantum hardware. The commercial success of cloud computing and services is supported by the elasticity provided to developers and the optimization of hardware usage provided to the hardware owners. Similar levels of flexibility and optimization should be possible in the quantum domain but additional research efforts are needed in quantum service engineering.

6. Conclusion and future works

In this paper, we have presented an implementation of a quantum microservice and the problem that arises from trying to integrate it in a hybrid microservices architecture. We have used Amazon Braket to test the implemented microservice on quantum hardware from three different vendors and to detect current limitations in the domain of hybrid classical-quantum microservices.

The performed experiments have allows us to clearly show the limitations of the current quantum computers platform for the development and exploitation of quantum microservices. Intense research efforts are still needed to bring the benefits of service-oriented computing and microservices to the quantum computing domain.

Since quantum software engineering is still a very young discipline, most of the areas that compose it are just starting to attract the interest of researchers, including hybrid microservices architectures. However, the change in the computing paradigm that implies quantum computing means that we cannot directly translate the techniques and tools of classical microservices and expect them to work flawlessly in the new environment. Putting a quantum algorithm inside a microservice is not enough to create a quantum microservices, there needs to be an effort to generate new knowledge, techniques, methodologies,... that helps bridge the gap between classical microservices and the advantages of quantum computers.

Acknowledgments

This work has been partially funded by the project RTI2018-094591-B-I00 (MCI/AEI/FEDER,UE), the 4IE+ Project (0499-4IE-PLUS-4-E) funded by the Interreg V-A España-Portugal (POCTEP) 2014-2020 program, by the Department of Economy, Science and Digital Agenda of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

[1] A. Steane, Quantum computing, Reports on Progress in Physics 61 (1998) 117.
[2] J. Preskill, Quantum computing in the nisq era and beyond, Quantum 2 (2018) 79.
[3] E. R. MacQuarrie, C. Simon, S. Simmons, E. Maine, The emerging commercial landscape of quantum computing, Nature Reviews Physics 2 (2020) 596–598.
[4] B. Sodhi, Quality attributes on quantum computing platforms, arXiv preprint arXiv:1803.07407 (2018).
[5] A. McCaskey, E. Dumitrescu, D. Liakh, T. Humble, Hybrid programming for near-term quantum computing systems, in: 2018 IEEE International Conference on Rebooting Computing (ICRC), IEEE, 2018, pp. 1–12.
[6] A. J. McCaskey, D. I. Lyakh, E. F. Dumitrescu, S. S. Powers, T. S. Humble, Xacc: a system-level software infrastructure for heterogeneous quantum–classical computing, Quantum Science and Technology 5 (2020) 024002.
[7] N. Dragoni, S. Giallorenzo, A. L. Lafuente, M. Mazzara, F. Montesi, R. Mustafin, L. Safina, Microservices: yesterday, today, and tomorrow, Present and ulterior software engineering (2017) 195–216.
[8] M. Piattini, G. Peterssen, R. Pérez-Castillo, J. L. Hevia, M. A. Serrano, G. Hernández, I. G. R. de Guzmán, C. A. Paradela, M. Polo, E. Murina, L. Jiménez, J. C. Marqueño, R. Gallego, J. Tura, F. Phillipson, J. M. Murillo, A. Niño, M. Rodríguez, The talavera manifesto for quantum software engineering and programming, in: Short Papers Proceedings of the 1st International Workshop on the QuANtum SoftWare Engineering & pRogramming, Talavera de la Reina, Spain, February 11-12, 2020, volume 2561 of *CEUR Workshop Proceedings*, 2020, pp. 1–5.
[9] O. Zimmermann, Microservices tenets, Computer Science-Research and Development 32 (2017) 301–310.
[10] J. Bogner, A. Zimmermann, Towards integrating microservices with adaptable enterprise architecture, in: 2016 IEEE 20th International Enterprise Distributed Object Computing Workshop (EDOCW), IEEE, 2016, pp. 1–6.

[11] J. Bogner, J. Fritzsch, S. Wagner, A. Zimmermann, Microservices in industry: insights into technologies, characteristics, and software quality, in: 2019 IEEE International Conference on Software Architecture Companion (ICSA-C), IEEE, 2019, pp. 187–195.
[12] A. Sill, The design and architecture of microservices, IEEE Cloud Computing 3 (2016) 76–80.
[13] L. Chen, Microservices: architecting for continuous delivery and devops, in: 2018 IEEE International conference on software architecture (ICSA), IEEE, 2018, pp. 39–397.
[14] M. Rahaman, M. M. Islam, A review on progress and problems of quantum computing as a service (qcaas) in the perspective of cloud computing, Global Journal of Computer Science and Technology (2015).
[15] J. Zhao, Quantum software engineering: Landscapes and horizons, CoRR abs/2007.07047 (2020). URL: https://arxiv.org/abs/2007.07047. arXiv:2007.07047.
[16] M. Piattini, G. Peterssen, R. Pérez-Castillo, Quantum computing: A new software engineering golden age, ACM SIGSOFT Softw. Eng. Notes 45 (2020) 12–14. URL: https://doi.org/10.1145/3402127.3402131. doi:10.1145/3402127.3402131.
[17] J. Barzen, F. Leymann, M. Falkenthal, D. Vietz, B. Weder, K. Wild, Relevance of near-term quantum computing in the cloud: A humanities perspective, in: D. Ferguson, C. Pahl, M. Helfert (Eds.), Cloud Computing and Services Science - 10th International Conference, CLOSER 2020, Prague, Czech Republic, May 7-9, 2020, Revised Selected Papers, volume 1399 of *Communications in Computer and Information Science*, Springer, 2020, pp. 25–58. doi:10.1007/978-3-030-72369-9_2.
[18] K. Wild, U. Breitenbücher, L. Harzenetter, F. Leymann, D. Vietz, M. Zimmermann, TOSCA4QC: two modeling styles for TOSCA to automate the deployment and orchestration of quantum applications, in: 24th IEEE International Enterprise Distributed Object Computing Conference, EDOC 2020, Eindhoven, The Netherlands, October 5-8, 2020, IEEE, 2020, pp. 125–134. doi:10.1109/EDOC49727.2020.00024.
[19] G. G. Guerreschi, A. Y. Matsuura, QAOA for Max-Cut requires hundreds of qubits for quantum speed-up, Scientific Reports 2019 9:1 9 (2019) 1–7. URL: https://www.nature.com/articles/s41598-019-43176-9. doi:10.1038/s41598-019-43176-9.
[20] M. Streif, M. Leib, Comparison of QAOA with Quantum and Simulated Annealing (2019). URL: https://arxiv.org/abs/1901.01903v1. arXiv:1901.01903.
[21] A. Peruzzo, J. McClean, P. Shadbolt, M.-H. Yung, X.-Q. Zhou, P. J. Love, A. Aspuru-Guzik, J. L. O'Brien, A variational eigenvalue solver on a quantum processor, Nature Communications 5 (2013). URL: https://arxiv.org/abs/1304.3061v1. doi:10.1038/ncomms5213. arXiv:1304.3061.
[22] J. R. McClean, J. Romero, R. Babbush, A. Aspuru-Guzik, The theory of variational hybrid quantum-classical algorithms, New Journal of Physics 18 (2015). URL: https://arxiv.org/abs/1509.04279v1. doi:10.1088/1367-2630/18/2/023023. arXiv:1509.04279.
[23] S. Boixo, T. Albash, F. M. Spedalieri, N. Chancellor, D. A. Lidar, Experimental signature of programmable quantum annealing, Nature communications 4 (2013) 1–8.
[24] R. Wille, R. Van Meter, Y. Naveh, Ibm's qiskit tool chain: Working with and developing for real quantum computers, in: 2019 Design, Automation & Test in Europe Conference & Exhibition (DATE), IEEE, 2019, pp. 1234–1240.
[25] R. H. Warren, Adapting the traveling salesman problem to an adiabatic quantum computer,

Quantum information processing 12 (2013) 1781–1785.

[26] R. H. Warren, Solving the traveling salesman problem on a quantum annealer, SN Applied Sciences 2 (2020) 1–5. URL: https://doi.org/10.1007/s42452-019-1829-x. doi:10.1007/s42452-019-1829-x.

[27] A. Matsuo, Y. Suzuki, S. Yamashita, Problem-specific Parameterized Quantum Circuits of the VQE Algorithm for Optimization Problems, arXiv (2020). URL: http://arxiv.org/abs/2006.05643. arXiv:2006.05643.

[28] K. Srinivasan, S. Satyajit, B. K. Behera, P. K. Panigrahi, Efficient quantum algorithm for solving travelling salesman problem: An IBM quantum experience, arXiv (2018). URL: http://arxiv.org/abs/1805.10928. arXiv:1805.10928.

[29] J. W. Ohlmann, B. W. Thomas, A compressed-annealing heuristic for the traveling salesman problem with time windows, INFORMS Journal on Computing 19 (2007) 80–90.

[30] C. Papalitsas, T. Andronikos, K. Giannakis, G. Theocharopoulou, S. Fanarioti, A qubo model for the traveling salesman problem with time windows, Algorithms 12 (2019) 224.

[31] P. Date, R. Patton, C. Schuman, T. Potok, Efficiently embedding QUBO problems on adiabatic quantum computers, Quantum Information Processing 18 (2019) 117. URL: https://doi.org/10.1007/s11128-019-2236-3. doi:10.1007/s11128-019-2236-3.

[32] A. Mahasinghe, R. Hua, M. J. Dinneen, R. Goyal, Solving the Hamiltonian Cycle Problem using a Quantum Computer, in: ACM International Conference Proceeding Series, Association for Computing Machinery, New York, NY, USA, 2019, pp. 1–9. URL: https://dl.acm.org/doi/10.1145/3290688.3290703. doi:10.1145/3290688.3290703.

[33] C. Durr, P. Hoyer, A Quantum Algorithm for Finding the Minimum (1996). URL: http://arxiv.org/abs/quant-ph/9607014. arXiv:9607014.

[34] A. P. Adelomou, E. G. Ribe, X. V. Cardona, Using the Parameterized Quantum Circuit combined with Variational-Quantum-Eigensolver (VQE) to create an Intelligent social workers' schedule problem solver, arXiv (2020). URL: http://arxiv.org/abs/2010.05863. arXiv:2010.05863.

Appendix G

Hybrid Classical-Quantum Software Services Systems: Exploration of the Rough Edges

Authors: *David Valencia, Jose Garcia-Alonso, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo.*

Publication type: *Conference paper.*

Conference: *International Conference on the Quality of Information and Communications Technology (QUATIC).*

Year of publication: *2021.*

DOI: *10.1007/978-3-030-85347-1_17*

2021 GGS Class (Rating): *Work in Progress.*

Hybrid Classical-Quantum Software Services Systems: Exploration of the Rough Edges

David Valencia, Jose Garcia-Alonso(✉), Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan Manuel Murillo

Social and Pervasive Innovation Lab (SPILab), University of Extremadura, Avda. de la Universidad s/n, 10003 Cáceres, Spain
{davaleco,jgaralo,javirojo,enrique,jberolm,juanmamu}@unex.es
http://spilab.es/

Abstract. The development that quantum computing technologies are achieving is beginning to attract the interest of companies that could potentially be users of quantum software. Thus, it is perfectly feasible that during the next few years hybrid systems will start to appear integrating both the classical software systems of companies and new quantum ones providing solutions to problems that still remain unmanageable today. A natural way to support such integration is Service-Oriented Computing. While conceptually the invocation of a quantum software service is similar to that of a classical one, technically there are many differences. To highlight these differences and the difficulties to develop quality quantum services, this paper takes a well-known problem to which a quantum solution can be provided, integer factorization, and the Amazon Braket quantum service platform. The exercise of trying to provide the factorization as a quantum service is carried out. This case study is used to show the rough edges that arise in the integration of classical-quantum hybrid systems using Service-Oriented Computing. The conclusion of the study allows us to point out directions in which to focus research efforts in order to achieve effective Quantum Service-Oriented Computing.

Keywords: Quantum services · Classical services · Quality

1 Introduction

Quantum computing is starting to establish itself as a commercial reality [15]. Several major computing corporations have already built working quantum computers, there are tens of quantum programming languages and simulators, and real quantum computers can already be used by the general public through the cloud. All this is motivating software development companies to take the first steps by launching their own proposals for the integral development of quantum software [2,22,23,25,31]. All of these signals are an urgent call to software engineers to prepare and enroll to sail the quantum seas.

A. C. R. Paiva et al. (Eds.): QUATIC 2021, CCIS 1439, pp. 225–238, 2021.
https://doi.org/10.1007/978-3-030-85347-1_17

It is generally assumed that on the way to a new world in which software systems are mostly quantum there will be a transition time in which classical and quantum systems must not only coexist but collaborate by interacting with each other [27]. This is what has been called classical-quantum hybrid systems [16,17]. The advances provided by software engineering in the last two decades allow us to affirm that a natural way to approach such collaborative coexistence is by following the principles of service engineering and service computing.

Among the reasons for this, two can be highlighted. On the one hand, as hardware technology matures and achieves more affordable costs, it is reasonable to think that companies will be inclined to use quantum infrastructure and quantum software as a service, as they are used to do nowadays with classical computing resources. On the other hand, it is reasonable to think that, at least initially, quantum systems will be used to solve only those parts of problems that cannot be solved by classical architectures, while those parts of problems that are already efficiently solved by classical architectures will continue to be treated as before. A natural way to achieve these quantum solutions is by consuming quantum services.

Conceptually, the invocation of a quantum program is similar to that of a classical service. A piece of software needs a result to be produced by a quantum system and to do so it consumes a service. For the sake of service engineering principles, such an invocation should even be agnostic of whether the service that will return the result is quantum or not. Technically, however, the invocation of a quantum service is very different from that of a classical service and still poses a challenge today. This is due to the inherent nature of quantum computing, meaning that a quantum service differs from classical services in which it includes entanglement and superposition of solutions, and will collapse to a single solution when interacting with external world, leading to having a probability amplitude associated to the results obtained upon observations of the quantum system.

Servitizing a quantum piece of software, namely converting it in a service endpoint that can be invoked through a standard service request, is possible with the existing technology. However, in the current status of quantum software it means eliminating most of the advantages that made Service-Oriented Computing a commercial success. Specially, those related with software quality like composability, modularity, maintainability, reusability, etc.

The reasons for this are multiple. First and foremost, the specificity of each architecture makes quantum algorithms and their parameters dependent on the specific quantum hardware in which they will be executed. But also, the return of the result of a quantum process is subject to errors or does not support the intermediate verification of results (due to the system collapse). Thus, different quantum architectures require very different skillsets. For example, circuit based quantum programming require developers to know the details of quantum gates [31], while quantum annealing programming requires to adapt the problem to that specific metaheuristic [3]. Consequently, invoking a quantum program in an agnostic way is impossible today and violates all the principles of service engineering. All above highlights the need for the development of Quantum Service Engineering.

In this paper we explore the current state of quantum software engineering from a service-oriented point of view. The integer factorization problem [11,20] is used to illustrate the different problems that arise when a quantum piece of code is tried to be used as a service. Amazon Braket[1], the quantum computing service offered by Amazon as part of their AWS suite is used as the services platform. Amazon is globally recognized as the leader company in services technology and through Braket they offer access to quantum computers from three different hardware providers. Using this platform as the basis for quantum services development, we identify the problems and limitations of current technology using the lessons learned from service-oriented computing. The paper provides an exploration of the problems to be addressed pointing out different research directions for the development of a future Quantum Service Engineering.

In order to do that, the rest of the paper is organized as follows. Section 2 details this work background in both fields service-oriented computing and quantum software development. Section 3 addresses the servitization of quantum software using Amazon Braket. Section 4 lists the main limitations found in today technology that limits the benefits of quantum services. Section 5 details the most relevant related works. And finally, Sect. 6 presents the paper conclusion and future works.

2 Background

Service-oriented computing is a paradigm that utilizes services as the fundamental elements for developing software [21]. One of its pillars is Service Oriented Architecture (SOA) that proposes the implementation of complex software solutions through the use of a set of services that are composed and choreographed [7]. The basic composition mechanism is the service call that allows a service to be invoked from another piece of code (potentially another service) agnostically with respect to the place, technology or architecture of the invoked service. The services can thus be maintained, evolved, replaced and reused independently without affecting the software that invokes them. It is precisely these properties what makes them especially attractive to create quality software. Over the last two decades, service-oriented computing and SOA in general, and web services in particular, have been at the center of intense research [4] leading to monolithic software being gradually replaced by service-based software run in the cloud.

The success of Service-Oriented Computing has been possible, to a great extent, thanks to the development of Cloud Computing as a paradigm that aims to provide reliable and customized dynamic computing environments [29]. Some of the main reasons behind the success of the cloud includes: the ability for companies to better control their costs, since they do not have to buy, upgrade and maintain expensive hardware and only pay for their use; and the flexibility and scalability provided by cloud vendors that allow companies to instantly increase or decrease their hardware capabilities according to their needs. These have made the cloud one of the most successful business models of the last

[1] https://aws.amazon.com/braket/.

decades. Recent estimations calculate that, in the USA only, cloud computing contributed with approximately 214 billion dollars in value-added to the GDP and 2.15 million jobs in 2017 [9].

Given these numbers is not a surprise that current quantum computers, which are still a very expensive hardware to build and operate, are being offered following this model. In its current form, most quantum computers can be accessed through the cloud in a model called by some researchers Quantum Computing as a Service (QCaaS) [26]. This model can be compared to the classical Infrastructure as a Service (IaaS) model offered in cloud computing. QCaaS allows developers to access some of the world existing quantum computers, nevertheless, this access is very dependent of the specific hardware and developers must have great proficiency in Quantum Computing to benefit from its advantages.

To increase the abstraction level of QCaaS, there are multiple ongoing research efforts. From a commercial perspective, platforms like the above mentioned Amazon Braket provide a development environment for quantum software engineers or, like QPath[2], an ecosystem that covers a wide range of possible applications by integrating the software classical and quantum worlds in a quantum development and application life-cycle platform for high-quality quantum software.

From a more academic perspective, a significant number of works are starting to appear in the field of quantum software engineering [24,32]. These works focus on translating the lessons learnt in classical software engineering to improve the quality of quantum software. However, as far as the authors know, very few works focus on the perspective of service engineering for quantum and hybrid software.

However, some works are starting to appear in this domain, like [1] where Quantum application as a Service (QaaS) is proposed to narrow the gap between classical service engineering and quantum software. Works like this reveal the need to focus on a service oriented approach for the development of quantum services.

3 Quantum Servitization: The Amazon Braket Case

To address the current state of quantum services, in this paper we have decided to use Amazon Braket. Amazon defines Braket as a fully managed quantum computing service. Specifically, Braket provides a development environment to build quantum algorithms, test them on quantum circuit simulators, and run them on different quantum hardware technologies.

Given that Amazon is currently the global leader regarding cloud computing and services technologies through AWS, Braket seems a good alternative to develop quantum services. Nevertheless, since the state of quantum software development is roughly the same in the different existing platforms, we expect similar results to the ones presented in this paper if the quantum services were developed on a different platform.

[2] https://www.quantumpath.es/.

The basic building block of service-oriented computing is a service, defined as a self-describing, platform-agnostic computational element that support rapid, low-cost composition of distributed applications [21]. However, Braket is not directly prepared to offer the developed quantum algorithms as services that can be invoked through an endpoint to compose a more complex application.

This shortcoming can be addressed by wrapping the quantum algorithm in a classical service. This implies including a classical computer to run the classical service that, in turn, invokes the quantum computer. As far as the authors know, there is currently no way of directly invoking a quantum algorithm as a service. Figure 1 shows an example of this approach. One of the simplest and well-known quantum circuits, the one used to create Bell states between two qubits is wrapped by a Flask[3] service. This Flask service can be deployed in a classical computer and provides a simple way to include quantum algorithms in a complex service-oriented solution.

Next, we present a more complex quantum algorithm used as a case study to identify the problems and limitations of current technology from the perspective of Service-Oriented Computing.

3.1 Integer Factorization Case Study

In order to make the analysis as broad and interdisciplinary as possible, we have decided to select a problem well-known by the scientific community working in quantum computing. At the same time, the selected problem is simple enough to be comprehended by any newcomer. Between the several applications that satisfy both conditions, we have decided to tackle on Integer Factorization, more precisely with a particular application of the later denoted Prime Factorization. As we all know, although this fundamental problem in number theory is computationally hard, it is not believed to belong to the NP-hard class of problems [11]. Nonetheless, it is a problem that has been used as a basic hardness assumption for cryptographic algorithms, such as the famous RSA algorithm. Thus, integer factorization and identification of new methods to address this task acquire an important role in information security.

There are multiple proposals and algorithms for the solution of this problem, being the most famous Shor's algorithm [20]. This algorithm is normally described in terms of quantum gates and circuits, suitable for development and execution on machines such as IBM's Q computing chip [8], but when considering other approaches to quantum computing, such as Adiabatic Quantum Computing based on concepts such as quantum annealing, it is not possible to implement Shor's algorithm directly. Nonetheless, other algorithms have been proposed for prime factoring, such is the case of the algorithm proposed by Wang et al. in [28]. Thus, in the studies conducted on this paper these will be the algorithms proposed for integer factorization: Shor's algorithms for quantum machines programmed with quantum circuits and gates, such as Rigetti's [19] and IonQ's

[3] https://flask.palletsprojects.com/.

```python
from flask import Flask, request, jsonify, send_file
from flask_cors import CORS
import matplotlib.pyplot as plt

from braket.circuits import Circuit
from braket.devices import LocalSimulator

app = Flask(__name__)
CORS(app)

@app.route('/execute', methods=["get"])
def execute_quantum_task():
    bell = Circuit().h(0).cnot(control=0, target=1)
    device = LocalSimulator()
    result = device.run(bell, shots=1000).result()
    counts = result.measurement_counts

    plt.bar(counts.keys(), counts.values())
    plt.xlabel('bitstrings')
    plt.ylabel('counts')
    plt.savefig("result.png")

    return send_file("result.png", mimetype='image/png')

if __name__ == '__main__':
    app.run(host="localhost", port=33888)
```

Braket libraries for quantum computing

Classical wrapping service

Quantum algorithm

Fig. 1. Quantum algorithm wrapped by a classical service

[12]; and integer factorization based on quantum annealing for adiabatic quantum machines such as D-Wave's [10].

These algorithms also serve as an illustration of a problem derived of the relative novelty of quantum computing and its different existing implementations. Namely, the nonexistence of algorithms with do-it-yourself characteristics. This is mainly due to the complex nature of the problems addressed by quantum computing and to the proximity of the algorithms with the underlying hardware used. This context is producing problems similar to those of the 60's software crisis [18], where each algorithm was designed for each particular computing hardware, many times having to recreate the algorithms for each new machine or even for each new increment of the problem. A reminiscent of this is found, for example, when having to generate a new circuit in Shor's algorithm for primes to be factorized. Although this is done relatively easy by using algorithms to generate these circuits automatically, for the great majority of possible users of quantum computing, the ability of being able to create these types of "meta-algorithms" is beyond their capabilities, complicating the expansion of quantum computing usage out of the specialized field. Thus, it is necessary to offer solutions to non-specialized users for the utilization of quantum computing, such as the case of deployment of quantum services which allow to hide the complexity to users, only providing with entry end-points and returning the results of the execution.

3.2 Integer Factorization in Amazon Braket

To illustrate the actual situation of quantum services that can be developed on Amazon Braket we have translated the above mentioned integer factorization algorithms to this platform.

At the moment of writing this paper Braket support three different quantum computer simulators and real quantum computers from three different hardware vendors. Specifically, the supported quantum computers include two vendors whose development is based on quantum circuits, Rigetti and IonQ, and one vendor based on quantum annealing, D-Wave. The integer factorization algorithms have been tested in all supported quantum machines and simulators.

Since the supported simulators are also based on quantum circuits, Shor's algorithm has been used in both, simulators and quantum circuits hardware. Figure 2 shows a fragment of the quantum period-finding subroutine of Shor's algorithm implemented using Amazon Braket. The complete circuit for Shor's algorithm can be executed without changes in the three simulators and the two circuit based computers supported by Braket. Nevertheless, is interesting to note that the measurement and reinitialization of qubits supported by many other existing simulators, and that can be therefore found in public implementations of Shor's algorithm, are not supported by Braket. In the figure, this part of the algorithm is left commented as an example. This difference with other existing solutions causes that the implementation presented here only works on certain occasions. Shor's algorithm can be adapted to avoid the use of these operations which means additional efforts to adapt one of the most well-known algorithms to the specifics of a given quantum platform.

Although, the quantum circuit would be the same regardless of the quantum hardware or simulator used, the way in which the algorithm is invoked changes depending on where it will be run. Figure 3 shows the Braket invocation code for the three simulators and the two quantum computers supported. As can be seen in the Figure, using the local simulator is the most straightforward invocation. To run the algorithms in the other simulators an s3 (Amazon simple storage system) destination has to be defined, where results will be stored, alongside a timeout for polling these results (if polling timeout is too short, results may not be returned within the polling time). Finally, for running the algorithm on real quantum computers a recovery task has to be defined. The quantum algorithm execution is an asynchronous operation and the developer is in charge of consulting the results when ready.

Finally, the code has to change significantly to run integer factorization in an adiabatic quantum machine, such as D-Wave's, since they are based on the adiabatic theorem closely related to quantum annealing. Thus, the mapping challenge differs from gate-based machines rendering quantum circuits inappropriate. Figure 4 shows the Braket code to factorize the number 21 using a D-Wave quantum machine.

```
def period(a,N, selected_device="LocalSimulator"):
    global Ran_Quantum_period_finding
    Ran_Quantum_period_finding = 1
    num_qubits = 5
    C_reg = [0,0,0]
    cr = C_reg
    qc = Circuit()
    Shor1 = qc
    Shor1.x(0)
    Shor1.h(4)
    Shor1.h(4)
#   Shor1.measure(4,C_reg[0]) #TODO operation not implemented
#   # Reinitialize to |0>
#   Shor1.reset(4) #TODO operation not implemented

    Shor1.h(4)
    for k in range(2):
        cmod(Shor1,a)
    if C_reg[0] == 1:
        Shor1.rz(4,pi/2.0)
    Shor1.h(4)

    Shor1.h(4)
    cmod(Shor1,a)
    if C_reg[1] == 1 :
        Shor1.rz(4,pi/2.0)
    if C_reg[0] == 1 :
        Shor1.rz(4,pi/2.0)
    Shor1.h(4)

    result = run_on_device(Shor1, selected_device)

    counts = result.measurement_counts
```

Fig. 2. Fragment of the quantum circuit needed to run Shor's algorithm in Amazon Braket

These examples, although small, are enough to remark the current limitations of quantum software from the point of view of service-oriented computing.

4 Current Limitation of Quantum Services

The analysis carried out during and after the experiments allows us to conclude that there is some roughness, limitations and problems that arise when a quantum piece of software is expected to be provided as a service. The mentioned limitations are not related to the fact that quantum services cannot be built but to the fact that, by implementing quantum services with current service technologies, the potential benefits of Service-Oriented Computing are lost. Such roughness can be classified into three different types depending on their nature.

```
if(selected_device=="LocalSimulator"):
    device = LocalSimulator()
    return device.run(circuit, shots=1000).result()
elif (selected_device=="SV1"):
    device = AwsDevice("arn:aws:braket:::device/quantum-simulator/amazon/sv1")
    return device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=24*60*60).result()
elif (selected_device=="TN1"):
    device = AwsDevice("arn:aws:braket:::device/quantum-simulator/amazon/tn1")
    return device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=24*60*60).result()

elif (selected_device=="Rigetti"):
    device = AwsDevice("arn:aws:braket:::device/qpu/rigetti/Aspen-8")
    task = device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=5*24*60*60)
    return recover_task_result(task)
elif (selected_device=="IonQ"):
    device = AwsDevice("arn:aws:braket:::device/qpu/ionq/ionQdevice")
    task = device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=5*24*60*60)
    return recover_task_result(task)
```

Fig. 3. Fragment of the Amazon Braket code to invoke the Shor's algorithm in different devices

```
sampler = BraketDWaveSampler(s3_folder,'arn:aws:braket:::device/qpu/d-wave/DW_2000Q_6')
sampler_embedding=EmbeddingComposite(sampler)
h={'s1': 580, 's2': 420, 's3': 144, 's4': 128}
J={('s1','s2'): 152, ('s1','s3'): -144, ('s1','s4'): -512, ('s2','s3'): 16,('s2','s4'):  -512, ('s3','s4'): 128}
sampleset=sampler_embedding.sample_ising(h,J,num_reads=100)
```

Fig. 4. Fragment of the Amazon Braket code to run the integer factorization algorithm in a D-Wave device

First, those related to the impossibility of abstracting the service from the architecture in which they are executed. Second, those associated with shortcomings of the actual abstractions to express or conceive architectures of quantum services. Finally, a third category related to the lack of support infrastructure for quantum services execution. The rest of this section delves into each of these categories.

In the case of the first category, problems related with the impossibility of abstracting the service from the architecture in which they are executed, they can be directly connected to vendor locking. This creates many different complications when generating and deploying services, such as, different types of parameters depending on the underlying machine to execute the code, as can be seen in the previous examples (see Figs. 3 and 4). In particular, when considering quantum annealing, the architecture itself restricts the specification of the problems. In this particular machine, the specification must be formulated using a QUBO or Ising form (see Fig. 4), defining it by means of graphs with valued vertex and valued links between these vertex. Any high order interrelation such as those found on terms involving 3 or greater number of variables must be mathematically transformed to simpler 2 variables related terms, a task with great complexity due to the necessity of ample and profound comprehension of the problem and dexterity on mathematical knowledge and tools.

Another difficulty of this category lies in the results generated. This is linked to the underlying physical phenomena that serve as base for the quantum architecture, such as the case of ion traps or quantum chips. Thus, apart from the well-known situation where the algorithms must be run several times to ensure statistical certainty adding a probability term to the results, depending on the architecture one must work with a panoply of solutions ranging from energy levels of solutions to "simple" probabilities and cases. This is directly incompatible with the philosophy of services.

Thus, to tackle these particular problems, the science of quantum services has to determine ways to abstract the algorithms and their results of the particularities of the machines.

Continuing with the categories, in the case of problems associated with shortcomings of the actual abstractions to express or conceive architectures of quantum services, this could be related to the misconception of directly using classical software abstractions for quantum software development. Reality posses that these abstractions are, in the best case, limited or directly inappropriate to express quantum services architectures. For example, the transparency and feature hiding typical of services cannot be achieved, even when working with solutions thought to serve as a simplification such as Amazon Braket. In other words, taking as starting point code developed in a well-known quantum programming language, almost standard of fact, such as Qiskit [31], the migration of the code to Amazon bracket's platform forces a conversion of code to the particular solution, having to generate new code and not doing a simple change of gates or functions denomination, along with different forms of invocations depending on the architecture selected to execute the code. This is a subset of a bigger drawback of quantum computing algorithms such are defined nowadays, first, having to accommodate the problems to new formulations to be used on quantum computing, such as the case of changing from integer factorization to period finding in the case of Shor's algorithm. Second, in many cases it is necessary "almost" significant modifications of the algorithm for each significant step of the problem size, i.e. different circuits for Shor's algorithm for factoring 15, 143 and so on. In order to work on this and further develop quantum services, it is necessary to rethink actual software development for quantum computing, having to abandon easy-to-carry preconceptions and contemplate the possibility and necessity of new quantum software engineering strategies.

Lastly, the problems related to the lack of general infrastructure for quantum services execution induces some situations that make it difficult to further implement and deploy quantum services. Such is the case of not being able to deploy quantum code on a quantum machine and only being able to execute it through remote invocations, along with other aspects related on how to manage the business side of quantum services, such as uptime, usage, and so on. Thus, quantum service researchers will have to further explore the transformations needed to evolve from small number of quantum machines owned by few enterprises to quantum cloud ecosystems fully available to a more general public.

5 Related Works

Due to the young nature of the quantum software engineering discipline, there is still not a lot of works focusing on quantum servitization. Nevertheless, some researchers are staring to delve in this area.

Works like [13] start to explore the potential of quantum services in the cloud and the research opportunities of quantum as a service. Some of the research opportunities presented are similar to the problems detected in this work. Specifically, the different implementations of the same quantum algorithms between different vendors or the problems to deploy quantum services in quantum computers.

Further exploring the deployment of quantum services, in [30] authors propose the use of TOSCA for quantum services. TOSCA is a standard for automating the deployment and orchestration of cloud applications. In this work, the authors define an extension to allow TOSCA to deploy quantum software. This proposal is similar to the work presented here in the sense that, since quantum applications must be newly deployed for each invocation, a classical computer is needed to host and deploy them. In our case, our wrapping classical service, as shown in Fig. 1, meets both function, hosting and deploying the quantum algorithm when invoked, but also converting the quantum algorithm in a service that can be included in a service-oriented architecture.

From a commercial perspective, along with Amazon Braket, there are other proposals also related to the simplification and homogenization of quantum access to machines and services. Such is the case of Azure Quantum [6], the counterpart of Amazon Braket. Azure Quantum not only includes Microsoft and IonQ, but also other partners such as Honeywell, Quantum Circuits Inc., 1Qloud and Toshiba. Azure Quantum provides a quantum development kit that allows the unification of an heterogeneous set of hardware and software solutions.

Similarly, other companies and software developers are creating high level development environments, toolkits and APIs to increase the abstraction level of quantum software. For example, IBM proposes IBM Quantum [5], although it only allows developers to run quantum algorithms in IBM quantum hardware or simulators. While other focus on specific domains like quantum machine learning [10]. However, as far as the authors know they do not provide any advance on quantum services over Amazon Braket.

Moreover, to be able to offer quality quantum services is not enough to simplify the development and deployment of quantum algorithms. Other aspects of quality service engineering [14] cannot be overlooked. Specifically, works needs to be done in the areas of orchestration, testing, security... of quantum services.

6 Conclusion and Future Works

In this paper we have presented an analysis of current quantum software from the point of view of Service-Oriented Computing. We have used Amazon Braket to deploy quantum services by wrapping them on a classical service and used the integer factorization problem to show the differences of running the same service on different quantum hardware, even when doing it under the common umbrella of Braket.

This experiment has allowed us to clearly present the current limitations in building and using quantum services. We have organized these limitations under three different categories and argued that intensive research efforts are needed to bring the benefits of Service-Oriented Computing to the quantum world.

Due to the young nature of quantum software engineering most areas in this discipline, including Service-Oriented Computing, are still giving their first steps. Nevertheless, the paradigm change that underlies quantum computing implies that there cannot be a direct translation of proposals and techniques. Running quantum algorithms as traditional services is not enough to bring the benefit of Service-Oriented Computing to the quantum era. There needs to be an effort to generate new techniques, methodologies and tools that bring all these benefits, already shown by the cloud and service computing, to quantum software and services.

Acknowledgements. This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014–2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

1. Barzen, J., Leymann, F., Falkenthal, M., Vietz, D., Weder, B., Wild, K.: Relevance of near-term quantum computing in the cloud: a humanities perspective. In: Ferguson, D., Pahl, C., Helfert, M. (eds.) CLOSER 2020. CCIS, vol. 1399, pp. 25–58. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-72369-9_2
2. Bergholm, V., et al.: Pennylane: automatic differentiation of hybrid quantum-classical computations. arXiv preprint arXiv:1811.04968 (2018)
3. Boixo, S., Albash, T., Spedalieri, F.M., Chancellor, N., Lidar, D.A.: Experimental signature of programmable quantum annealing. Nat. Commun. **4**(1), 1–8 (2013)
4. Bouguettaya, A., et al.: A service computing manifesto: the next 10 years. Commun. ACM **60**(4), 64–72 (2017)
5. Cross, A.: The IBM Q experience and QISKIT open-source quantum computing software. APS March Meet. Abs. **2018**, L58-003 (2018)
6. Cuomo, D., Caleffi, M., Cacciapuoti, A.S.: Towards a distributed quantum computing ecosystem. IET Quantum Commun. **1**(1), 3–8 (2020)
7. Endrei, M., et al.: Patterns: service-oriented architecture and web services. IBM Corporation, International Technical Support Organization, New York (2004)
8. Haring, R., et al.: The IBM blue GENE/Q compute chip. IEEE Micro **32**(2), 48–60 (2011)
9. Hooton, C.: Examining the economic contributions of the cloud to the United States economy. Report. Internet Association, Washington, DC (2019)
10. Hu, F., Wang, B.N., Wang, N., Wang, C.: Quantum machine learning with d-wave quantum computer. Quantum Eng. **1**(2), e12 (2019)

11. Jiang, S., Britt, K.A., McCaskey, A.J., Humble, T.S., Kais, S.: Quantum annealing for prime factorization. Sci. Rep. **8**(1), 1–9 (2018)
12. Kielpinski, D., Monroe, C., Wineland, D.J.: Architecture for a large-scale ion-trap quantum computer. Nature **417**(6890), 709–711 (2002)
13. Leymann, F., Barzen, J., Falkenthal, M., Vietz, D., Weder, B., Wild, K.: Quantum in the cloud: application potentials and research opportunities. In: Proceedings of the 10th International Conference on Cloud Computing and Service Science (CLOSER 2020), pp. 9–24. SciTePress (2020). https://doi.org/10.5220/0009819800090024
14. Li, S., et al.: Understanding and addressing quality attributes of microservices architecture: a systematic literature review. Inf. Softw. Technol. **131**, 106449 (2021)
15. MacQuarrie, E.R., Simon, C., Simmons, S., Maine, E.: The emerging commercial landscape of quantum computing. Nat. Rev. Phys. **2**(11), 596–598 (2020)
16. McCaskey, A., Dumitrescu, E., Liakh, D., Humble, T.: Hybrid programming for near-term quantum computing systems. In: 2018 IEEE International Conference on Rebooting Computing (ICRC), pp. 1–12. IEEE (2018)
17. McCaskey, A.J., Lyakh, D.I., Dumitrescu, E.F., Powers, S.S., Humble, T.S.: XACC: a system-level software infrastructure for heterogeneous quantum-classical computing. Quantum Sci. Technol. **5**(2), 024002 (2020)
18. Moguel, E., Berrocal, J., García-Alonso, J., Murillo, J.M.: A roadmap for quantum software engineering: applying the lessons learned from the classics. In: Pérez-Castillo, R., Piattini, M., Peterssen, G., Hevia, J.L. (eds.) Short Papers Proceedings of the 1st International Workshop on Software Engineering & Technology (Q-SET'20) co-located with IEEE International Conference on Quantum Computing and Engineering (IEEE Quantum Week 2020), (Online Conference) Broomfield, Colorado, USA, October 2020. CEUR Workshop Proceedings, vol. 2705, pp. 5–13. CEUR-WS.org (2020). http://ceur-ws.org/Vol-2705/short1.pdf
19. Motta, M., et al.: Determining eigenstates and thermal states on a quantum computer using quantum imaginary time evolution. Nat. Phys. **16**(2), 205–210 (2020)
20. Nielsen, M.A., Chuang, I.: Quantum computation and quantum information (2002)
21. Papazoglou, M.P.: Service-oriented computing: concepts, characteristics and directions. In: Proceedings of the Fourth International Conference on Web Information Systems Engineering, WISE 2003, pp. 3–12. IEEE (2003)
22. Pérez-Castillo, R., Piattini, M.: The quantum software engineering path. In: Pérez-Castillo, R., Piattini, M., Peterssen, G., Hevia, J.L. (eds.) Short Papers Proceedings of the 1st International Workshop on Software Engineering & Technology (Q-SET'20) co-located with IEEE International Conference on Quantum Computing and Engineering (IEEE Quantum Week 2020) Broomfield, Colorado, USA, October 2020. CEUR Workshop Proceedings, vol. 2705, pp. 1–4. CEUR-WS.org (2020). http://ceur-ws.org/Vol-2705/invited1.pdf
23. Pérez-Castillo, R., Serrano, M.A., Piattini, M.: Software modernization to embrace quantum technology. Adv. Eng. Softw. **151**, 102933 (2021)
24. Piattini, M., Peterssen, G., Pérez-Castillo, R.: Quantum computing: A new software engineering golden age. ACM SIGSOFT Softw. Eng. Notes **45**(3), 12–14 (2020)
25. Piattini, M., Serrano, M., Perez-Castillo, R., Petersen, G., Hevia, J.L.: Toward a quantum software engineering. IT Prof. **23**(1), 62–66 (2021)
26. Rahaman, M., Islam, M.M.: A review on progress and problems of quantum computing as a service (QCAAS) in the perspective of cloud computing. Glob. J. Comput. Sci. Technol. (2015)

27. Sodhi, B.: Quality attributes on quantum computing platforms. arXiv preprint arXiv:1803.07407 (2018)
28. Wang, B., Hu, F., Yao, H., Wang, C.: Prime factorization algorithm based on parameter optimization of Ising model. Sci. Rep. **10**(1), 1–10 (2020)
29. Wang, L., et al.: Cloud computing: a perspective study. New Gener. Comput. **28**(2), 137–146 (2010)
30. Wild, K., Breitenbücher, U., Harzenetter, L., Leymann, F., Vietz, D., Zimmermann, M.: TOSCA4QC: two modeling styles for TOSCA to automate the deployment and orchestration of quantum applications. In: 24th IEEE International Enterprise Distributed Object Computing Conference, EDOC 2020, Eindhoven, The Netherlands, 5–8 October 2020, pp. 125–134. IEEE (2020). https://doi.org/10.1109/EDOC49727.2020.00024
31. Wille, R., Van Meter, R., Naveh, Y.: IBM'S Qiskit tool chain: working with and developing for real quantum computers. In: 2019 Design, Automation & Test in Europe Conference & Exhibition (DATE), pp. 1234–1240. IEEE (2019)
32. Zhao, J.: Quantum software engineering: landscapes and horizons. CoRR abs/2007.07047 (2020). https://arxiv.org/abs/2007.07047

Appendix H

Social Events Analyzer (SEA): Un toolkit para minar Social Workflows mediante Federated Process Mining

Authors: *Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2021.*

Handle: *11705/JCIS/2021/027*

Social Events Analyzer (SEA): Un toolkit para minar Social Workflows mediante Federated Process Mining

Javier Rojo[1][0000−0001−9189−1133], José García-Alonso[1][0000−0002−6819−0299], Javier Berrocal[1][0000−0002−1007−2134], Juan Hernández[1][0000−0002−6343−7395], Juan M. Murillo[1][0000−0003−4961−4030], and Carlos Canal[2][0000−0002−8002−0372]

[1] University of Extremadura, Cáceres, Spain
{javirojo,jgaralo,jberolm,juanher,juanmamu}@unex.es
[2] Universidad de Málaga, Málaga, Spain
ccanal@lcc.uma.es

Abstract. La ingente cantidad de información recogida por los dispositivos móviles proporciona una visión de los distintos procesos que un usuario sigue en su día a a día. Estos procesos pueden ser analizados, con el fin de saber más acerca del usuario como individuo y como parte de distintos grupos sociales. Sin embargo, analizar eventos que están sujetos al comportamiento humano, donde el indeterminismo y la variabilidad prevalecen, no es sencillo. No existen, por lo tanto, técnicas sencillas que permitan discernir que usuarios pertenecen a un determinado grupo y cuales no, impidiendo crear Social Workflows solo con la información de aquellos usuarios que tienen algo en común. En esta demo presentamos Social Events Analyzer (SEA), un *toolkit* que permite analizar Social Workflows mediante Federated Process Mining. SEA proporciona modelos más fieles al comportamiento de los usuarios que conforman un Social Workflow y abre la puerta al uso de la minería de procesos como base para la creación de nuevos procedimientos automáticos adaptados al comportamiento de los usuarios.

Keywords: Process Mining · Pattern discovery · Social Workflows · Federated Process Mining.

1 Introducción

Los smartphones constantemente recopilan las distintas acciones de los usuarios [7]. Estas pueden modelarse como un proceso, permitiendo el análisis del comportamiento del usuario a través de la minería de procesos [3]. No solo a nivel individual, sino también considerando al usuario como parte de un grupo en el que todos sus miembros siguen un proceso o Social Workflow (SOW) común [5].

Sin embargo, las técnicas actuales no están preparadas para analizar Social Workflows de forma eficiente. Están diseñadas para extraer la realidad basándose en procesos bien definidos. Sin embargo, el comportamiento humano no suele ser determinista, sino muy variable [5]. Esto, que ya es un problema a nivel individual, es un problema aún mayor a nivel social. Cuando se integran las trazas de usuarios con comportamientos muy diferentes y se analiza el Social Workflow resultante, el resultado es un proceso que no aporta conocimiento real de ningún usuario ni del propio grupo.

Existen técnicas que permiten filtrar la variabilidad en el comportamiento de cada usuario [2], incluyendo en su proceso sólo los eventos y relaciones más frecuentes, estas técnicas no permiten saber que usuarios tienen comportamientos en común, filtrarlos y formar un Social Workflow solo con su información.

Estas son las razones que han guiado el desarrollo de SEA y de Federated Process Mining. SEA ofrece el conjunto de herramientas necesario para realizar minería de procesos sobre Social Workflows utilizando Federated Process Mining. En Federated Process Mining la minería de procesos se realiza en dos pasos: una primera fase de minería de procesos individual en el smartphone de cada usuario para filtrar qué usuarios forman parte de un Social Workflow y una segunda fase de minería de procesos sociales, tras agregar los datos filtrados anteriormente. El filtrado se realiza en base a una consulta que se envía a cada smartphone, donde se describe el comportamiento buscado en los usuarios. Para aquellos usuarios que cumplan con el comportamiento marcado en su modelo individual (el modelo descubierto con sus trazas en la primera fase), se comprueban una a una sus trazas y se envían al servidor solo aquellas que presentan el comportamiento buscado —de esta manera no es necesario comprobar todas las trazas si el comportamiento no aparece en el modelo. Federated Process Mining se basa en la premisa de que el comportamiento humano no es errático per se [4]. Por ello, analizar el comportamiento de cada usuario por separado antes de integrarlo mejora la representación de cada usuario en el Social Workflow y la del grupo de usuarios que lo componen en consecuencia. Federated Process Mining busca ofrecer una solución cuando se conoce el comportamiento de interés a priori —a diferencia de otras técnicas, como clustering, donde se tratan de descubrir comportamientos comunes no conocidos a priori.

Los beneficios del Federated Process Mining son varios. Gracias al uso de smartphones para realizar la primera fase de la minería, es posible reducir la cantidad de datos enviados al servidor —con la consiguiente reducción de la huella energética [1]—, reducir la carga computacional del servidor y preservar la privacidad de los usuarios. Además, gracias a una primera fase para filtrar qué usuarios pertenecen al Social Workflow en el que se está interesado, Federated Process Mining ofrece modelos sociales más compactos, donde sólo se representa la información que representa a los miembros de ese Social Workflow y que no pierden calidad respecto a los modelos generados con métodos clásicos de la minería de procesos.

SEA simplifica la realización de Federated Process Mining. Tanto manualmente, para extraer información de sus usuarios e interpretarla, como para la creación de sistemas automáticos, que empleen la información por si mismos para hacer recomendaciones o personalizar los procesos. Complementando a este documento, se muestra el uso de SEA sobre datos del ámbito de IoT[1].

[1] https://youtu.be/yJnJbZoefvQ

2 Social Events Analyzer (SEA)

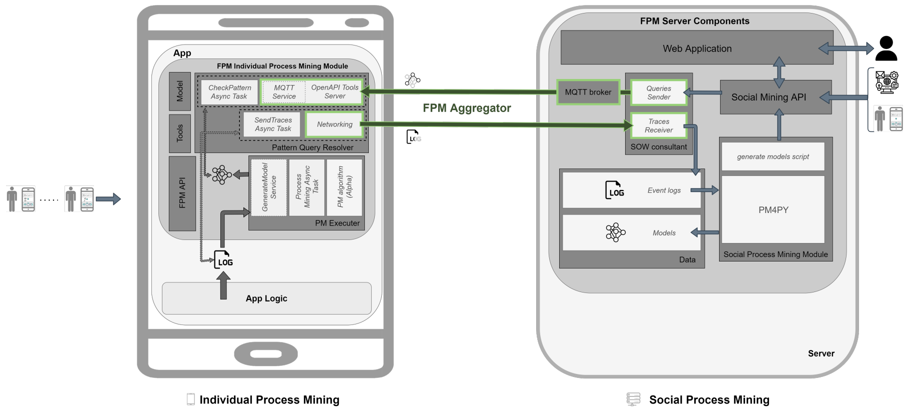


Fig. 1. Arquitectura del toolkit SEA.

La Figura 1 muestra los diferentes componentes de SEA. En ella se pueden encontrar los tres componentes principales de Federated Process Mining, que se dividen en una serie de subcomponentes, cada uno de ellos encargado de realizar tareas específicas dentro del workflow de Federated Process Mining.

Individual Process Mining component.[2] Este componente se despliega en cada uno de los smartphones. En concreto, SEA ofrece el módulo *FPM Individual Process Mining*, que debe ser incluido en la aplicación móvil que genera el registro de eventos —en formato .XES [6]. Cabe destacas el *PM executer*, encargado de la primera fase de minería de procesos individual, así como el *Pattern Query Resolver*, encargado de recibir las consultas del Social Process Mining y enviar las trazas que cumplen con el patrón de comportamiento.

Social Process Mining component.[3] Este componente se despliega en un servidor, y se encarga de crear las consultas y generar el modelo social con los datos de los usuarios. Entre los distintos subcomponentes que lo forman, destaca la *Social Mining API*, una API REST a la que terceros pueden conectarse para emplear los datos del Federated Process Mining. También se ofrece una *Web Application* con la que se pueden analizar los datos de forma no automática.

FPM Aggregator. Este componente, implementado como parte de los anteriores —resaltado en verde en la Figura 1—, es el que envía las consultas desde el *Social Mining component* a los smartphones. También es el que recoge las trazas de los usuarios y las almacena en el *Social Mining component.*

[2] https://bitbucket.org/spilab/individualpmmodule
[3] https://bitbucket.org/spilab/fpmserver/

3 Conclusiones y trabajos futuros

Social Events Analyzer (SEA) permite la realización de minería de procesos sobre Social Workflows, mediante lo que los autores de este trabajo denominan Federated Process Mining. Para ello, SEA ofrece una serie de componentes (*toolkit*) para los smartphones y el servidor donde se realiza la fase de minería social.

Gracias al uso de SEA y, por tanto, de Federated Process Mining, se consiguen optimizar los recursos necesarios para llevar a cabo la minería de procesos y se obtienen modelos más fieles a los procesos de un grupo social y de sus integrantes. Además, el uso de SEA para llevar a cabo minería de procesos acerca esta disciplina cada vez más a la creación de sistemas automáticos, con toma de decisiones o adaptación de sistemas de forma automática en base a la información de los procesos —como ya se hiciera con la minería de datos.

Es esto último en lo que se pretende seguir avanzando en el desarrollo de SEA y, por ende, de Federated Process Mining. También se valora la integración de los modelos individuales en lugar de las trazas mediante fusión de modelos o el uso de monitorización predictiva de procesos.

Agradecimientos

Este trabajo ha sido financiado por los proyectos 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020), RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), y UMA18-FEDERJA-180 (Junta de Andalucía/ATech/FEDER), por la Consejería de Economía, Ciencia y Agenda Digital de la Junta de Extremadura (GR18112, IB18030), la ayuda FPU19/03965, y el Fondo Europeo de Desarrollo Regional.

References

1. Berrocal, J., García-Alonso, J., Fernandez, P., Pérez-vereda, A., Hernandez, J., Canal, C., Murillo, J.M., Ruiz-Cortes, A.: Early evaluation of mobile applications' resource consumption and operating costs. IEEE Access **8**, 146648–146665 (2020)
2. Chapela-Campa, D., Mucientes, M., Lama, M.: Mining frequent patterns in process models. Information Sciences **472**, 235 – 257 (2019)
3. Dogan, O., Fernandez-Llatas, C., Oztaysi, B.: Process mining application for analysis of customer's different visits in a shopping mall. In: Advances in Intelligent Systems and Computing. vol. 1029, pp. 151–159. Springer Verlag (jul 2020)
4. Gonzalez, M.C., Hidalgo, C.A., Barabasi, A.L.: Understanding individual human mobility patterns. Nature **453**(7196), 779–782 (2008)
5. Görg, S., Bergmann, R.: Social workflows - Vision and potential study. Information Systems **50**, 1–19 (jun 2015)
6. Gunther, C.W., Verbeek, H.M.W., Dolech, D., Eindhoven, A.Z., Günther, C.W., Verbeek, E.: XES-standard definition. Tech. rep. (2014)
7. Rojo, J., Flores-Martin, D., Garcia-Alonso, J., Murillo, J.M., Berrocal, J.: Automating the interactions among iot devices using neural networks. In: 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops). pp. 1–6 (2020)

Appendix I

Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas (Summary)

Authors: *Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, Juan M Murillo.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2021.*

Handle: *11705/JCIS/2021/031*

Smart Nursing Homes: Self-Management Architecture Based on IoT and Machine Learning for Rural Areas (Summary)*

Daniel Flores-Martin(✉), Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan M. Murillo

Universidad de Extremadura, Cáceres, Spain
{dfloresm,javirojo,enrique,jberolm,juanmamu}@unex.es

Summary of the contribution

The rate of world population aging is increasing. This situation directly affects all countries socially and economically and, increasing their compromise and effort to improve the living conditions of this sector of society.

In environments with large influxes of elderly people the use of technology has shown promise in improving their quality of life. The use of smart devices allows people to automate everyday tasks and learn from them to predict future actions. Additionally, smartphones capture a wealth of information that allows to adapt to nearby actuators according to people's preferences and even detect anomalies in their behaviour. Current works are proposing new frameworks to detect these behaviours and act accordingly. However, these works are not focused on managing multi-device environments where sensors and smartphones data are considered to automate environments with elderly people or to learn from them. Also, the most of these works require a permanent Internet connection, so the full benefit of smart devices is not completely achieved.

In this work, we present an architecture that takes the data from sensors and smartphones in order to adapt the behaviour of the actuators of the environment. The architecture is implemented through a use-case based on a nursing home located in a rural area. Thanks to this work, the quality of life of the elderly is improved in a simple, affordable and transparent way for them.

Acknowledgments

This work was supported by 4IE+ project (0499_4IE_PLUS_4_E) funded by the Interreg V-A España-Portugal (POCTEP) 2014-2020 program, by the Spanish Ministry of Science, Innovation and Universities (RTI2018-094591-B-I00 project, and FPU17/02251 and FPU19/03965 grants), by the Department of Economy, Science and Digital Agenda of the Government of Extremadura (GR18112, IB18030) and by the European Regional Development Fund.

* This work has been published in Wireless Communications and Mobile Computing for Ambient Assisted Living, Vol 2021. Impact Factor: 1.819 DOI: https://doi.org/10.1155/2021/8874988

Appendix J

Quantum software as a service through a quantum API gateway

Authors: *Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo.*

Publication type: *Journal article.*

Journal: *IEEE Internet Computing.*

Year of publication: *2021.*

DOI: *10.1109/MIC.2021.3132688*

2021 JCR IF (Rank): *2.680 (Q2 43/110)*

Quantum Software as a Service Through a Quantum API Gateway

Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, and Juan Manuel Murillo, *University of Extremadura, 10003 Cáceres, Spain*

As quantum computers mature, the complexity of quantum software increases. As we move from the initial standalone quantum algorithms toward complex solutions combining quantum algorithms with traditional software, new software engineering methods and abstractions are needed. Nowadays, quantum computers are usually offered in the cloud, under a pay-per-use model, leading to the adoption of the service-oriented good practices that dominate the cloud today. However, specific adaptations are needed to reap the benefits of service-oriented computing while dealing with quantum hardware limitations. In this article, we propose the Quantum API Gateway—an adaptation of the API Gateway pattern that takes into account the fact that quantum services cannot be deployed as traditional services. Instead, the Quantum API Gateway recommends the best quantum computer to run a specific quantum service at run time. As proof of concept, we provide an implementation of the Quantum API Gateway for the Amazon Braket platform.

Quantum computing hardware is rapidly evolving. Different companies are introducing new quantum computers, and the number of qubits keeps increasing.[1] At the same time, new quantum algorithms are being discovered, with quantum software being applied to more domains.

Nevertheless, quantum computers are still costly to own and operate. To expedite the adoption of the quantum paradigm and increase the research efforts in this promising domain, most of the existing quantum computers are offered through the cloud via a pay-per-use model.[2]

The irrefutable success of cloud computing over the past years is demonstrated by recent estimations showing that, in the United States alone, cloud computing contributed approximately US$214 billion in value-added to the GDP and 2.15 million jobs in 2017.[3] This computing model gives companies better control over their costs since they do not have to buy, upgrade, and maintain expensive hardware—they only have to pay for the services they use. A similar model is emerging for quantum computing.

However, quantum software engineering is still in a very early stage.[4] This means that the benefits and advantages provided by cloud computing, which are easily exploited by traditional software, are more elusive when quantum software is involved.

At the moment, most quantum software systems are, indeed, hybrid systems in which quantum software parts coexist and cooperate with traditional software ones.[5] A natural way to approach such collaborative coexistence, especially in the cloud, is by following the principles of software engineering in the services domain and service-oriented computing. Conceptually, the invocation of a quantum piece of software is similar to that of a classical service. However, the current limitations of quantum cloud infrastructure do not allow developers to benefit from their software engineering expertise.

In this article, we propose, using a Quantum API Gateway, a software engineering solution, to simplify the development of hybrid systems that include quantum services. This API Gateway provides a way to treat quantum services as traditional services, so developers can easily integrate them into their processes and tools. At the same time, the Quantum API Gateway takes advantage of the current status of quantum cloud infrastructure, which provides unified access to

1089-7801
Digital Object Identifier 10.1109/MIC.2021.3132688
Date of publication 9 December 2021; date of current version 28 January 2022.

quantum computers from different vendors—to offer some additional benefits to quantum developers. Specifically, since quantum programs cannot be permanently deployed in a quantum computer—instead, they have to be deployed each time they are executed—the Quantum API Gateway offers a heuristic to determine the best quantum computer in which to deploy the quantum software at run time. Interestingly, this complexity is hidden from the service client. As proof of concept, this article provides an implementation of the Quantum API Gateway by using the services offered by the Amazon Braket Quantum platform.

QUANTUM SOFTWARE AS A SERVICE: STATE OF THE ART

As mentioned previously, most of the quantum computers available for researchers and developers are offered through the cloud in a pay-per-use model. Following a naming scheme similar to that used for traditional computing in the cloud, researchers started calling this model Quantum Computing as a Service (QCaaS).[6]

Given the current status of quantum computers, this access can be best compared with the traditional Infrastructure as a Service, where users directly interact with the physical resources in the cloud. Users can develop and execute quantum programs using a quantum programming language supported by the hardware they employ. The execution process involves sending the program to a scheduler that will, in time, send the code to the quantum computer whenever there is a timeslot available.

This has been the starting point for researchers to try to increase the abstraction level of quantum services. However, the early stage of quantum hardware and quantum software engineering techniques for quantum programs has to be considered. At the moment, rapid progress is being made in most areas of quantum software engineering, although most efforts have revolved around quantum programming and quantum programming languages. Additional efforts are still needed to consolidate the methods, processes, and techniques that will lead to quality, reusable quantum software.[7]

In the specific domain of quantum services, the Quantum Application as a Service[8] proposal is of particular interest. Its authors recommend wrapping all quantum application and deployment logic in a traditional application programming interface (API). This API can then take care of input data encoding and launching the quantum software in a QCaaS offering, thus simplifying the integration of the quantum program with traditional applications.

Similarly, Valencia *et al.*[9] proposed wrapping a quantum program in a classical service. When this service is called, the quantum software is deployed in a QCaaS offering at run time. This process allows developers to integrate their quantum algorithms into service-oriented solutions. This same idea was explored further in Rojo *et al.*'s work.[10] This work suggested the creation of quantum microservices with different endpoints for different QCaaS solutions, thus allowing developers to create complex hybrid solutions in which classical and quantum microservices coexisted.

All these proposals, however, focused on quantum software as traditional services, and thus suffered from a similar drawback. Traditional services can be deployed once in a server in the cloud and then called many times by different clients. However, as far as the authors know, currently there is no quantum computer in which this behavior could be replicated. Every time a quantum piece of code has to be executed, it needs to be deployed first. This increases the computational cost of running the software and disrupts the usual workflow of service-oriented solutions.

Some proposals are starting to emerge to address this issue. Wild *et al.*[11] proposed an extension to TOSCA, a well-known standard for the deployment and orchestration of cloud applications. This extension allows developers to create a deployment model that contains all the information needed to automate the deployment of quantum software in coordination with traditional services.

These proposals illustrate the interest in bringing the benefits of service-oriented computing to quantum software. However, the current state of quantum hardware and quantum software engineering does not support the abstraction level required to work with quantum software as services. Indeed, additional research efforts are necessary to bring both worlds together. In this work, we propose an adaptation of one of the better-known patterns in service-oriented computing, the API gateway. Our implementation brings some of the benefits of services to quantum software while also taking advantage of the current state of quantum hardware to optimize the deployment of quantum services.

QUANTUM API GATEWAY

An API Gateway is a service composition pattern developed to allow creating end-user applications based on the composition of different microservices. The API Gateway serves as the system's entry point, routing requests to the appropriate microservices. It can also invoke aggregate results, transform protocols, and implement shared logic.[12]

SIDEBAR: COMMERCIAL QUANTUM CLOUD PLATFORMS

From a commercial point of view, several companies involved in the development of quantum hardware are also interested in its potential as a cloud computing offering. Most of the biggest computing companies in the world are already offering cloud-based quantum computing solutions. IBM's Quantum Services,[1] Google's Quantum Computing Service,[2] or Microsoft's Azure Quantum[3] are the prime examples. These companies offer their quantum hardware and services through their own platforms—most of the time alongside access to quantum hardware and software from other vendors, unified through their own quantum development ecosystem.

Amazon follows a slightly different approach. As the market leader on cloud computing through AWS, Amazon also offers its own quantum cloud, Amazon Braket.[4] However, Amazon is not developing its own quantum hardware. Instead, Braket focuses on providing services over third-party quantum hardware.

A different approach is also followed by smaller quantum hardware companies like D-Wave.[5] These companies are developing their own quantum computers and offering their services through their own cloud platforms. However, at the same time, they are also integrated in the bigger companies' cloud platforms, in order to increase their reach.

REFERENCES

1. https://www.ibm.com/quantum-computing/services/
2. https://quantumai.google/quantum-computing-service
3. https://azure.microsoft.com/en-us/services/quantum/
4. https://aws.amazon.com/en/braket/
5. https://www.dwavesys.com/

Challenges and Problems

In this article, we propose an adaptation of the API Gateway to address some of the current problems in quantum services. Namely, since quantum services cannot be deployed on a quantum computer to be invoked several times, the Quantum API Gateway would be in charge of deploying the quantum service whenever a client requests it. Considering that this deployment incurs costs with every invocation, the Quantum API Gateway optimizes the deployment strategy. Whenever a quantum service is called, the Quantum API Gateway will decide at run time which of the available quantum computers is best suited for that particular execution, thus optimizing the quantum service invocation process.

To make this decision, the Quantum API Gateway will not only use any information available that is useful in this regard like quantum computers availability, economic cost of the quantum hardware usage, estimated response time, etc., but also current traits of quantum computers like qubit topology, error rate, or fidelity. The availability of this information is dependent on the quantum platform supporting the Quantum API Gateway and, currently, very limited. As quantum platforms mature, more of this kind of information will be provided to users, and therefore, the capabilities of the Quantum API Gateway will be increased.

Calling a Quantum Service

Figure 1 exemplifies the process of calling a quantum service through the proposed Quantum API Gateway, following the steps detailed in the following.

The process starts when a client needs to call one of the quantum services available through the Quantum API Gateway. As shown in step 1, the client needs to specify the service they are invoking, the input parameters of the service (if necessary), and the execution optimization parameters.

Considering the optimization parameters provided, the Quantum API Gateway determines which of the quantum computers available is best suited to attend to the current request. For this purpose, the quantum computer recommender requests all the information available to the QCaaS Provider (step 2), and this one sends it the updated status information of the available quantum hardware (step 3).

Once the best quantum computer to run a given service invocation is determined, the quantum service manager requests all the necessary information (step 4) to deploy the service to the selected quantum hardware with the appropriate input parameters (step 5).

Finally, once the service has finished its execution, the Quantum API Gateway receives the response offered by the selected quantum computers (step 6). Only then it sends back the results to the service client (step 7).

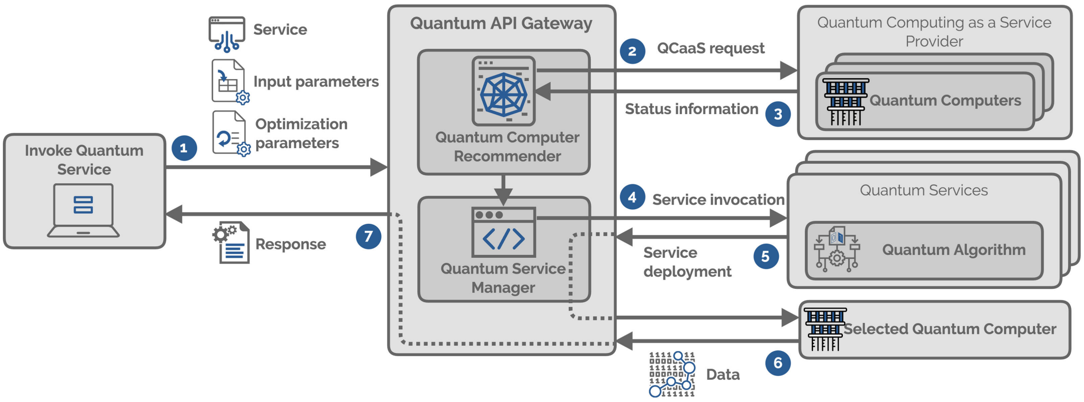


FIGURE 1. Quantum API Gateway—Service calling process.

This process allows choosing the most appropriate quantum computer at run time without significantly increasing the computational cost—since the quantum service would have to be deployed for each invocation anyway. To demonstrate the viability of this proposal, the following section presents an implementation of the Quantum API Gateway for the Amazon Braket platform.

QUANTUM API GATEWAY FOR AMAZON BRAKET

This article presents an implementation of the Quantum API Gateway concept for the Amazon Braket quantum computing platform using Python and Flask. This platform was selected because it offers an integral solution for executing quantum code in different quantum processors. The implementation of the API Gateway is available here.[a]

To determine the best quantum computer for each execution, the Quantum API Gateway takes into account parameters such as the type of code to be executed (gate-based or annealing), the number of qubits required to execute the service, the maximum economic cost for the execution (considering the number of shots needed), or the tradeoff between execution time and cost—to determine whether it is better to select the cheaper machine or the one that is estimated to give the results in the shortest possible time. These parameters are compared against a series of static and dynamic information that Braket offers regarding the quantum computers available to determine the best-suited one, following the algorithm detailed in Figure 2. Other traits of current quantum computers, such as qubit topology or error rate, are not offered programmatically by Braket; therefore, these cannot be taken into account. If the platform offers more information in the future, this could be integrated into the selection algorithm.

[a]https://github.com/frojomar/Quantum_API_Gateway

Insights and Key Contributions

By selecting the quantum computer for each execution, the implementation of the API Gateway provides the following advantages over the existing support for quantum services.

First, depending on the type of code to be executed, the API Gateway allows developers to choose at runtime (assuming that both implementations of the quantum service are available) between gate-based or annealing machines. In the case of gate-based machines, the number of qubits required is used to determine those with enough computing power. The number of qubits per machine is provided by Amazon Braket as static data.

The next step is to evaluate the cost per selected computer. To that end, the number of shots indicated by the developer, the cost per shot, and the desired maximum cost threshold are used—considering "shots" as the number of repetitions required to identify the solution and, hence, the results of the service execution.

In particular, the *economic cost* of the service execution is calculated as *cost per execution+(cost per shot*N shots)*. Those computers with a result below the indicated threshold are selected. The *cost per execution* and the *cost per shot* can be obtained from Amazon Braket.

Once the machines below the cost threshold have been selected, the Quantum API Gateway uses the Amazon Braket API to check the availability of the quantum computers that meet the requirements. This step is the most time-consuming step, since it

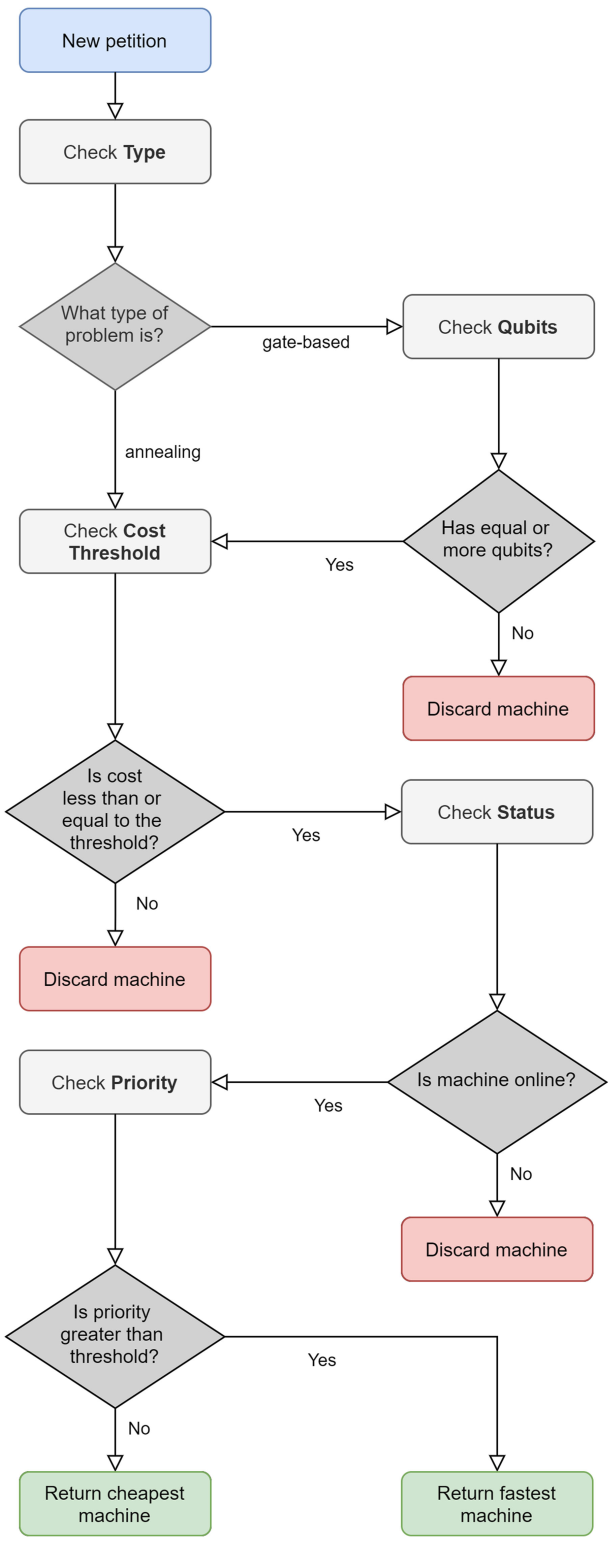


FIGURE 2. Quantum computer selection algorithm for Amazon Braket.

requires communicating with Amazon Braket to establish the actual status of each machine. That is why, it is performed at this point—once the machines meeting the developer's requirements have been selected. Only those machines with "ONLINE" status are selected for the next phase, in which the estimated execution time for each machine is calculated. Then, a tradeoff—*priority* in Figure 2—between the cost and the response time is used to select the machine in which the quantum service will be executed.

Calculation of the estimated execution time for each computer is based on the characteristics of the execution, its context (namely the day of the week and the time of the start of the execution), and the actual time taken by past executions performed on that computer. In addition, another time variable is added—related to the analysis of the previous executions as a time series. Thus, the resulting time contains both the waiting time in the machine's execution queue and the time required to execute the quantum service.

In any case, this implementation of the Quantum API Gateway is modular. Both the static and dynamic characteristics, as well as those taken into account when estimating the execution time, can be complemented with different parameters from other providers. Likewise, the method for analyzing the time estimation information could be replaced or parameterized with different values.

Execution Time Forecasting Model

The model employed to forecast the full execution time—waiting time plus execution time itself—has been developed with Keras. It uses the information available to calculate the execution time, in addition to the context parameters. The provided implementation uses two different models: one for gate-based and one for annealing machines. It has been divided into two models because each one includes specific parameters for each kind of machine.

Moreover, the execution time will depend not only on the characteristics of the specific execution but also on the task load of the quantum processor. For this reason, a temporal analysis is carried out on the last executions performed on each machine. Thus, the characteristics and the time required for each execution are taken into account to predict the execution time. This replaces the temporal analysis of the last minutes of evolution of the processor's workload—since, at the time of writing this article, Amazon Braket did not provide this parameter.

Deep learning techniques, such as neural networks, were used to make these predictions—specifically recurrent neural networks (RNNs),[13] since the

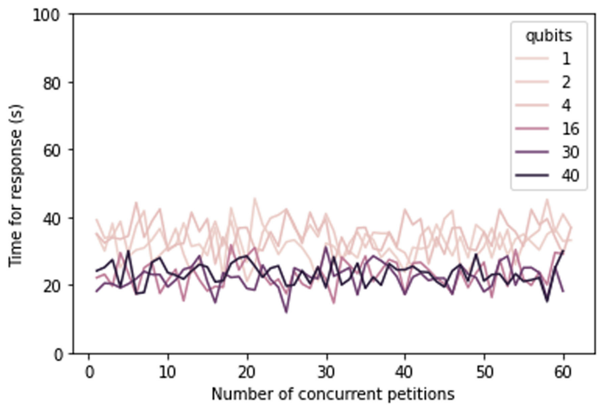


FIGURE 3. Execution time of Quantum API Gateway as a function of the concurrent petition.

analysis took into account a temporal dimension. These neural networks have the ability to maintain data memory. Long short-term memory, in particular, was chosen because its long-term memory is better than that of the classic RNNs. Due to space restrictions, no specific metrics of model quality are provided here. Any other network could be used instead of the proposed one without affecting the Quantum API Gateway behavior—it will only impact the time estimations for the execution of a quantum service.

Main Functionalities

To achieve the abovementioned behavior, the Quantum API Gateway provides two main functionalities implemented as endpoints: one to obtain recommendations on which quantum machine to run the service, and another to provide feedback on the time it took to complete an execution to improve the execution time estimation model. These endpoints are given as follows.

GET /execute: It executes the Quantum API Gateway optimization with the above-described input parameters and returns the best-suited computer to execute the code.

POST /feedback: It allows indicating the Quantum API Gateway the time required to execute the service in a specific computer, alongside the executed service's description—qubits and shots—and context variables—day of the week and time of the day—to improve the execution time estimation model.

Thanks to this, Quantum API Gateway offers developers a tool that enables their users to enjoy a quantum experience more adapted to their needs. When a quantum solution with the lowest possible cost is required, Quantum API Gateway will recommend running on the machine that offers the appropriate features with the lowest possible cost. When fast execution is required, it will recommend the one offering the shortest execution times. In any of these scenarios, the most adequate machine is always identified and provided. In addition, by developing Quantum API Gateway as a REST API, its integration with other service deployment tools is enhanced, improving its integration into current software development tools and methodologies.

VALIDATION

To demonstrate the feasibility of the Quantum API Gateway, we have tested its implementation using the services offered by Amazon Braket platform. The main goal of this validation was to test the delay caused by the inclusion of the Quantum API Gateway in the execution of a quantum service.

To this end, a series of concurrent requests were sent to the gateway, measuring the time it took for the gateway to respond. Specifically, up to 60 concurrent requests were sent. In this way, it was tested whether the time it took for the gateway to respond was stable or worsened as the number of simultaneous requests increased. Furthermore, this process was replicated with different qubit configurations.

Figure 3 shows the results obtained. It is noticeable that the gateway's performance was stable, regardless of the number of concurrent requests. Furthermore, the higher the number of qubits, the less time it took for the gateway to respond, again regardless of the number of concurrent requests. This is due to the decrease in the number of quantum computers that could address the petition for those with a sufficient number of qubits. Therefore, there were fewer computer whose real-time status had to be checked.

As can be seen in Figure 3, a request on the Quantum API Gateway took on average 26.671 s. Of these, 26.668 s (99.98% of the Quantum API Gateway time) were consumed in querying the real-time status of the different machines available through the Amazon Braket API. The execution of the recommendation algorithm took less than 0.01 s. The querying time could be significantly reduced by using a cache mechanism to check the status of the quantum computers—at the cost, however, of losing precision. Another possibility could be the platform providing a real-time API to check this information.

For the sake of brevity, a more detailed description of the validation process and the data obtained, alongside a Python3 Jupyter notebook for replication, can be found at the Quantum API Gateway repository mentioned previously.

CONCLUSION

As the complexity of quantum software increases, so does the need for software engineering methods and tools that enable developers to deal with such complexity. Since most of the current quantum computers are offered through the cloud, it is only natural that software engineers reach for the service-oriented toolbox that has already proved highly successful in the cloud. However, the current limitations of quantum hardware hinder the direct translation of these techniques. Specific adaptations are needed to deal with the particularities of quantum computers.

In this work, we have proposed an adaptation of the API Gateway service-oriented pattern. The Quantum API Gateway addresses the fact that services cannot be deployed on a quantum computer to be executed later. Instead, quantum services have to be deployed before each execution. The proposed Quantum API Gateway deals with this inconvenience by providing an optimization that allows developers to determine the best-suited quantum computer for each execution of a quantum service at run time.

To demonstrate the viability of the Quantum API Gateway, an implementation is provided for the Amazon Braket platform. This implementation takes into account the status of the different quantum computers integrated into the platform, the maximum cost allotted for the execution, and the estimated response time, among other parameters, to recommend the best-suited hardware for each service execution.

The validation performed shows the viability of the Quantum API Gateway, although better integration is needed with quantum computing platforms such as Amazon Braket. As quantum platforms evolve and more information is provided to developers regarding the status of the quantum hardware, the Quantum API Gateway could be adapted to provide better recommendations. At the same time, more complex heuristics could be developed for quantum hardware recommendation—taking into account additional parameters. Similarly, as quantum software evolves, more responsibilities could be placed on the Quantum API Gateway—as is the case with the traditional API Gateway.

ACKNOWLEDGMENTS

This work was supported in part by the projects Interreg V-A España-Portugal 2014-2020 under Grant 0499_4IE_PLUS_4_E and MCIU/AEI/FEDER, UE under Grant RTI2018-094591-B-I00, in part by Grant FPU19/03965, in part by the Department of Economy and Infrastructure of the Government of Extremadura under Grant GR18112 and Grant IB18030, and in part by the European Regional Development Fund.

REFERENCES

1. E. R. MacQuarrie, C. Simon, S. Simmons, and E. Maine, "The emerging commercial landscape of quantum computing," *Nature Rev. Phys.*, vol. 2, no. 11, pp. 596–598, 2020.
2. F. Leymann, J. Barzen, M. Falkenthal, D. Vietz, B. Weder, and K. Wild, "Quantum in the cloud: Application potentials and research opportunities," in *Proc. 10th Int. Conf. Cloud Comput. Serv. Sci.*, May 2020, pp. 9–24.
3. C. Hooton, "Examining the economic contributions of the cloud to the United States economy," Internet Assoc., Washington, DC, USA, Rep., Mar. 2019.
4. M. Piattini, G. Peterssen, and R. Pérez-Castillo, "Quantum computing: A new software engineering golden age," *ACM SIGSOFT Softw. Eng. Notes*, vol. 45, no. 3, pp. 12–14, 2020.
5. A. J. McCaskey, D. I. Lyakh, E. F. Dumitrescu, S. S. Powers, and T. S. Humble, "XACC: A system-level software infrastructure for heterogeneous quantum-classical computing," *Quantum Sci. Technol.*, vol. 5, no. 2, 2020, Art. no. 024002.
6. M. Rahaman and M. M. Islam, "A review on progress and problems of quantum computing as a service (QCAAS) in the perspective of cloud computing," *Glob. J. Comput. Sci. Technol.*, vol. 15, no. 4, pp. 15–18, 2015.
7. J. Zhao, "Quantum software engineering: Landscapes and horizons," 2020, *arXiv:2007.07047*.
8. J. Barzen, F. Leymann, M. Falkenthal, D. Vietz, B. Weder, and K. Wild, "Relevance of near-term quantum computing in the cloud: A humanities perspective," in *Cloud Computing and Services Science - 10th International Conference, CLOSER 2020, Prague, Czech Republic, May 7-9, 2020, Revised Selected Papers, Ser. Communications in Computer and Information Science*, D. Ferguson, C. Pahl, and M. Helfert, Eds., vol. 1399. Cham, Switzerland: Springer, 2020, pp. 25–58.
9. D. Valencia, J. Garcia-Alonso, J. Rojo, E. Moguel, J. Berrocal, and J. M. Murillo, "Hybrid classical-quantum software services systems: Exploration of the rough edges," in *Quality of Information and Communications Technology - 14th International Conference, QUATIC 2021, Proceedings, Ser. Communications in Computer and Information Science*. Cham, Switzerland: Springer, 2021, pp. 225–238.

10. J. Rojo, D. Valencia, J. Berrocal, E. Moguel, J. García-Alonso, and J. M. M. Rodriguez, “Trials and tribulations of developing hybrid quantum-classical microservices systems,” in *2nd Quantum Softw. Eng. Technol. Workshop, QSET'21, CEUR Workshop Proc.*, vol. 3008, 2021, pp. 38–53.
11. K. Wild, U. Breitenbücher, L. Harzenetter, F. Leymann, D. Vietz, and M. Zimmermann, “TOSCA4QC: Two modeling styles for TOSCA to automate the deployment and orchestration of quantum applications,” in *Proc. 24th IEEE Int. Enterprise Distrib. Object Comput. Conf.*, Eindhoven, The Netherlands, 2020, pp. 125–134.
12. D. Taibi, V. Lenarduzzi, and C. Pahl, “Architectural patterns for microservices: A systematic mapping study,” in *Proc. CLOSER*, 2018, pp. 221–232.
13. S. Bhavya and A. S. Pillai, “Prediction models in healthcare using deep learning,” in *Advances in Intelligent Systems and Computing*, vol. 1182, Cham, Switzerland: Springer, Dec. 2019, pp. 195–204. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-49345-5_21

JOSE GARCIA-ALONSO is currently an Associate Professor with the Department of Informatics and Telematics System Engineering, University of Extremadura, Badajoz, Spain, and a co-founder of the startups Gloin and Viable. His research interests include quantum software engineering, eHealthCare, eldercare, mobile computing, context-awareness, and pervasive systems. He received the Ph.D. degree from the University of Extremadura (with European Mention) in 2014. He is the corresponding author of this article. Contact him at jgaralo@unex.es.

JAVIER ROJO is currently a Ph.D. student with the University of Extremadura, Badajoz, Spain, where he has a predoctoral position through a grant for the formation of university professors from the Spanish Ministry of Science, Innovation and Universities. His research interests include software engineering, eHealth, pervasive computing, and mobile computing. He received the M.Sc. degree in computer science from the University of Extremadura in 2021. He is a member of the IEEE. Contact him at javirojo@unex.es.

DAVID VALENCIA is a currently a postdoctoral researcher with the University of Extremadura, Badajoz, Spain. His research interests include quantum computing, parallel and distributed computing, and software engineering. He received the M.Sc. and Ph.D. degrees in computer science from the University of Extremadura in 2004 and 2010, respectively. Contact him at davaleco@unex.es.

ENRIQUE MOGUEL is currently an Assistant Professor at the University of Extremadura Badajoz, Spain. His research interests include web engineering, smart systems, and quantum computing. He received the M.Sc. degree from University Carlos III, Getafe, Spain, in 2010 and the Ph.D. degree from the University of Extremadura in 2018, both in computer science. Contact him at enrique@unex.es.

JAVIER BERROCAL is currently an Associate Professor with the Department of Informatics and Telematics System Engineering, University of Extremadura, Badajoz, Spain, and a co-founder of the startup Gloin. His research interests include mobile computing, context awareness, pervasive systems, the Internet of Things, and fog computing. He received the Ph.D. degree from the University of Extremadura (with European Mention) in 2014. Contact him at jberolm@unex.es.

JUAN MANUEL MURILLO is currently a Full Professor of Software Engineering at the University of Extremadura, Badajoz, Spain, and a co-founder of the startups Gloin and Viable. His research interests include quantum software engineering, software architectures, mobile computing, and cloud computing. He received the Ph.D. degree in computer science from the University of Extremadura in 2001. Contact him at juanmamu@unex.es.

Appendix K

Blockchain-Supported Health Registry: The Claim for a Personal Health Trajectory Traceability and How It Can Be Achieved

Authors: *Javier Rojo, Juan Hernández, Sumi Helal, Juan M Murillo, José García-Alonso.*

Publication type: *International workshop paper.*

Workshop: *Fourth International Workshop on Gerontechnology.*

Year of publication: *2022.*

DOI: *10.1007/978-3-030-97524-1_3*

Blockchain-Supported Health Registry: The Claim for a Personal Health Trajectory Traceability and How It Can Be Achieved

Javier Rojo[1](✉), Juan Hernández[1], Sumi Helal[2], Juan M. Murillo[1], and José García-Alonso[1]

[1] University of Extremadura, Cáceres, Spain
{javirojo,juanher,juanmamu,jgaralo}@unex.es
[2] University of Florida, Gainesville, FL, USA
helal@cise.ufl.edu

Abstract. The digitalization of health processes is a reality. Each time, there are more services and institutions generating and interacting with the health data of a patient. This put in manifest some deficiencies of actual health systems, such as the need for data no longer revolve around the institutions that generate them and start to revolve around the users or patients to whom they belong. Otherwise, patients will end up losing focus and control of their data, which is distributed among different information systems. To address this, many researchers around the world have proposed software solutions that integrate a patient's data into a global view, even though it is still stored in a distributed way in the systems that generate it. However, the mere integration of data does not allow a patient to have real knowledge of the entire life cycle of her different records. To this end, data integration solutions must go a step further and convert the structure that maintains the overall view of a patient's health, her Personal Health Trajectory, into a registry ensuring the traceability of the patient's health. As a result, patients will have a real understanding of everything that surrounds their health data and true patient-centered healthcare systems will be one step closer.

Keywords: Data integration · Data interoperability · eHealth · Blockchain · Health traceability

1 Introduction

Today's society is a digitalized one. All being susceptible of be digitalized is translated to electronic support that processes and store the attached information. In this context, health processes, as well as their input and output data, are being digitalized [8,21]. Concepts such as Electronic Health Records (EHRs) [11] and Personal Health Records (PHRs) [16] have arisen in the last few years. Particularly, the lasts have been widely employed recently to store any kind

J. García-Alonso and C. Fonseca (Eds.): IWoG 2021, LNBE, pp. 22–33, 2022.
https://doi.org/10.1007/978-3-030-97524-1_3

of health information about patients—including those generated by intelligent health devices such as Internet of Medical Things (IoMT) [4,6,19] or Web of Medical Things (WoMT) devices [15].

The broader capability of each new electronic support to store more diverse sources' health information highlights the need to offer mechanisms to patients in order to collect all their health information provided by different agents [9,18]—understanding by agents different types of healthcare entities or connected smart devices generating health data. Moreover, it can even arise *data-ownership*'s doubts in the patients, who are not confident about which systems store information about their health, as well as each of them does not have full knowledge about the interactions involving their data [22].

Due to all this, the advantages of digitalizing health processes are mitigated. Not having a way to access all her health data makes it difficult for a patient to manage it and apply its ownership's rights—since she is the real owner of her health data [18]. Health data can be generated, but they can also be modified in case there is an error in them and even deleted [12]—if requested by the patient to whom they belong. For any of these actions, the patient should have a way to keep track of and be aware of all the changes that occur in her health reality.

The first step to obtain empowers patients and allowing them to be aware of all concerning their data is to obtain a complete vision of their health trajectory [20]. In this sense, the most promising proposals in the literature are the ones using blockchain to obtain a data structure referencing where each health record of the user are stored [1,17]—due to its distributed nature, as well as its guarantees on data security and privacy [2,12]. Authors of this paper has contributed to it with previous works [18]. However, although these proposals offer unified access and the integration of each patient's health data, none of them take advantage of having a structure per patient to employ it as a registry of changes in the patient's health reality, rather than just as a directory to access their data.

It is clear that having this registry would help the patient to have greater control over their data, to validate the authenticity of the test data—detecting addictions, modifications or undue deletions of data—and to have complete traceability of the patient's health reality—as is done in other domains, such as food's traceability [3]. That is the reason why this paper makes efforts in the definition of this registry and proposes a theoretical implementation of it.

The obtainment of this registry contributes to the achievement of the *Personal Health Trajectory* of patients, proposed by the authors of this paper in previous works [20]. In addition, having a data structure such as the one proposed in this paper, new patient-centered health systems—instead of current institution-centered ones—come to a step closer [20].

The rest of the paper is structured as follows: Sect. 2 shows the motivations of this work and related work. Section 3 presents the concept of Personal Health Trajectory and its relationship to the health's registry presented in this paper. Then, Sect. 4 deeps on how to obtain this registry by means of their implementation with blockchain. Section 5 brings a brief discussion over the consequences and real applications of this registry. Finally, in Sect. 6 the conclusions of this work and some future lines of research are exposed.

2 Motivations and Related Works

In the current health systems, the data about its patients is stored in an isolated way. Data stored in the information system of a health system—or in cloud services from smart devices—for a patient is not aware of data stored in other health systems' information systems for the same patient [9]. Therefore, if a patient interacts with many of these health systems or uses smart devices to monitor her health, multiple, fragmented representations of her health reality are generated [18]. Further the duplicity and inconsistencies problems concerning these multiple, fragmented representations, this also makes difficult for patients to manage their health reality and be aware of all operations involving it.

As a first step to achieve it, each time more proposals try to integrate the patients' health data in a unique, global vision. On the one hand, proposals such as that of Spil et al. [23] or that of Kyazze et al. [13] advocate for the integration of health data physically integrating it on the same storage system. On the other hand, proposals such as that of Zhang et al. [24], advocate for the interoperability of data stored in a distributed way—reducing the intrusiveness of the first type of proposals—even using the same technology of the first ones. In this line, proposals using blockchain as support to enable this interoperability have arisen—being this one of the main suggested applications of this technology on health domain in last years[2,12]. Proposals such as that of Roehrs et al. [17] or that of Chen et al. [1] present the creation of a blockchain-supported data structure per patient that stores in their blocks references to where it is stored each of their health records. Jalali et al. [10] propose the Personicle concept, a chronicle of live events related with health of users. To generate it, they propose a framework integrate, store, and analyze data from heterogeneous data streams.

Moreover, the authors of this paper had been working on their own proposal defining the blockchains' federation concept [18], having a blockchain per patient with access to all their records and another upper blockchain that allows health professionals to locate the blockchains of patients sharing their data.

Although all these proposals achieve a solution to the problem of the multiple, fragmented visions of the health reality of a patient, all of them are only considering operations of the addition of new records. Some of them even affirm that health data does not need to be modified or deleted after their addition [1], so only the addition of data must be registered in the global vision. Despite this, as some studies on blockchain for eHealth affirm [12], these others operation can be necessary for some situations. This is solved by proposals that do not integrate physically records, but they make them interoperable through an additional data structure. Nevertheless, this has other implications, such as the global vision is not aware of what is happening in records—i.e., blockchain's security properties are applied to the global vision, but not to the records referenced by it.

Proposals generating this global vision could take advantage of having a data structure with all patient's health data to offer new mechanisms that empower patient with the control on her data—and even that improve the security of it [14]. This single, global view, in which the all health data of a patient are integrated, could offer users greater control over what is happening at any given moment in their medical history: the traceability of their health data.

Achieving this traceability, beyond the simple integration of health data, can be useful for the patient for multiple reasons. It will give the user complete control over what happens to his health data: when it is added, when it is modified, or when it is deleted—as well as where and by whom these actions are performed. In addition, it also allows verification of the authenticity of the records. For example, by saving a value computed with the content of a record at the time of adding or modifying it, it is possible to check whether its content has been maliciously altered at the time of accessing it. Likewise, it is possible to check whether a record has been deleted without the patient's consent or, at least, without the patient's knowledge. All this leads to greater empowerment of the data on the part of the patient and greater security for the records.

The fact of using a blockchain to perform traceability is not new. There are already many proposals in other fields where blockchain is used as a registry to ensure the traceability of elements such as food. In the case of alimentary traceability, public blockchains—where anyone can read—are employed to share the different stages by which a concrete aliment has passed since it was collected until it is on the hand of consumer [5]. Even within the health domain, no proposal talking about health traceability are found, in the field of smart health and eHealth there are already proposals that talk about the need to offer a certain grade of security in health data that could be achieved by means of health traceability [7,25]. Specifically, the works found claims for the need to ensure personal health data provenance, as well as right confirmation, by means of smart contracts, and the control of who is performing changes in health information to prevent malicious activity by means of the control of access keys' sharing.

Other proposals such as that of Li et al. [14] limit their application only to the insurance of health data security and not to the complete traceability of it. From the analysis of these works, it can be concluded that health traceability required a private approach where only patient to which health data belongs and their authorized users can access their health data traceability—in contrast to the public approach followed in alimentary traceability. This analysis reveals also that none of the proposals found trying to offer a full traceability solution such as this offered in other domains—e.g., the commented alimentary traceability. Each proposal faces only concrete parts of this traceability: data provenance, content validation, malicious accesses, among others.

The authors of this article believe that providing health data traceability and providing mechanisms for integrating distributed health data are intimately linked—as they have been trying to illustrate throughout this section. That is why they want to take advantage of the data structure already generated by many proposals—including their own—to integrate or make interoperable distributed data and enable it to perform the tasks of health data traceability. To this end, it is proposed to refocus the information to be stored, obtaining a solution that solves both problems. In this way, the aim is to bring closer the arrival of patient-centered health systems that are more complete without complicating their integration into current information systems.

3 Extending Personal Health Trajectory for Traceability

Personal Health Trajectory is a concept that arises in the minds of this paper's authors in previous researches [20], when they try to offer a solution to the problems of actual institution-centered health systems from the patient perspective. Among others, this concept implies the creation of new patient-centered health systems, where the information revolves around and in virtue of this, and not of the institutions—as it has up to now. In order to make this possible, the need to the creation of a data structure where all the patient's distributed data are aggregated into a complete view of the patient's health throughout her life arises—see Fig. 1.

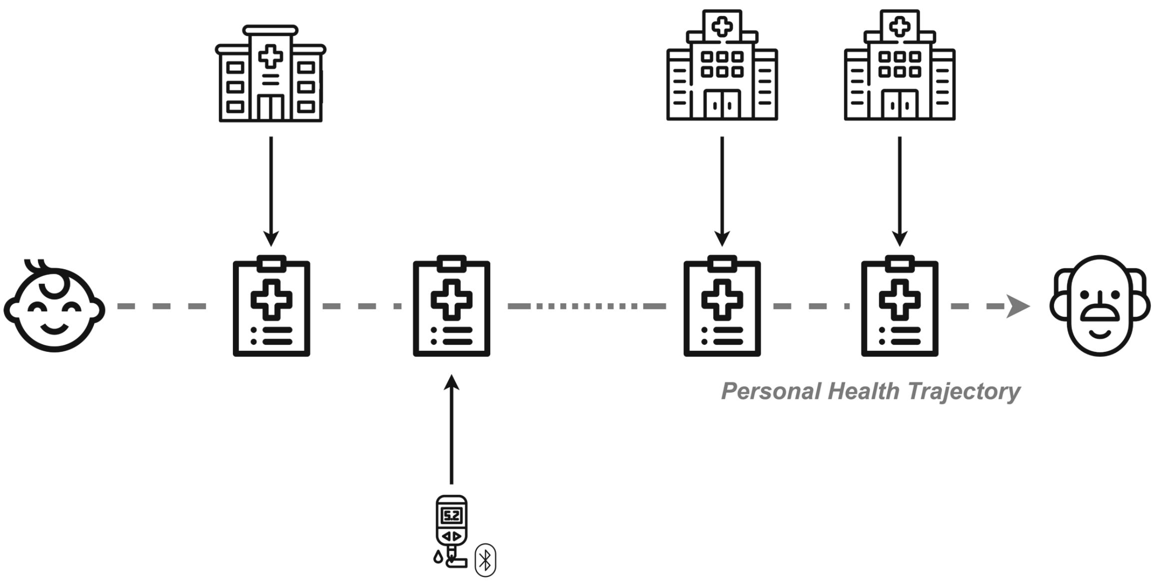


Fig. 1. Personal Health Trajectory concept

However, as motivated in the previous section, this structure does not have to remain just a system of links to patient records. It can take advantage of them to record all the changes that occur in the patient's health reality. Following the scheme of CRUD operations (create, read, update, and delete) that can be performed on the data, these would be: read (GET), add (POST), modify (PUT), and delete (DELETE).

Moreover, next to each operation associated with a health record, a value can even be stored to reflect the status of that record at the time a written operation—the creation or updating of the record—is recorded in its Personal Health Trajectory. In this way, it can be guaranteed that, if the state of the record is not the same as the one saved the last time this record was referenced in the Personal Health Trajectory, someone has spoiled it.

On the other hand, all this leads to empowerment of their health data by the patient. By belonging to the Personal Health Trajectory, the patient can control who has access to it and who does not. Thanks to traceability mechanisms, such as the one mentioned above, all those who interact with or generate patient health records without going through their Personal Health Trajectory can be considered unidentified users. Therefore, the authenticity and purpose of this data cannot be verified. Thus, this data may be treated with a different level of caution than data written by recognized agents—those to whom the patient has allowed access to the Personal Health Trajectory to write their changes.

4 Blockchain as Physical Support for Personal Health Trajectory Traceability

One of the most widely used technologies for the creation of the data structure that integrates patient health data is blockchain. Specifically, this is the main technology used in the proposal of the authors of this paper to create their Personal Health Trajectory [18].

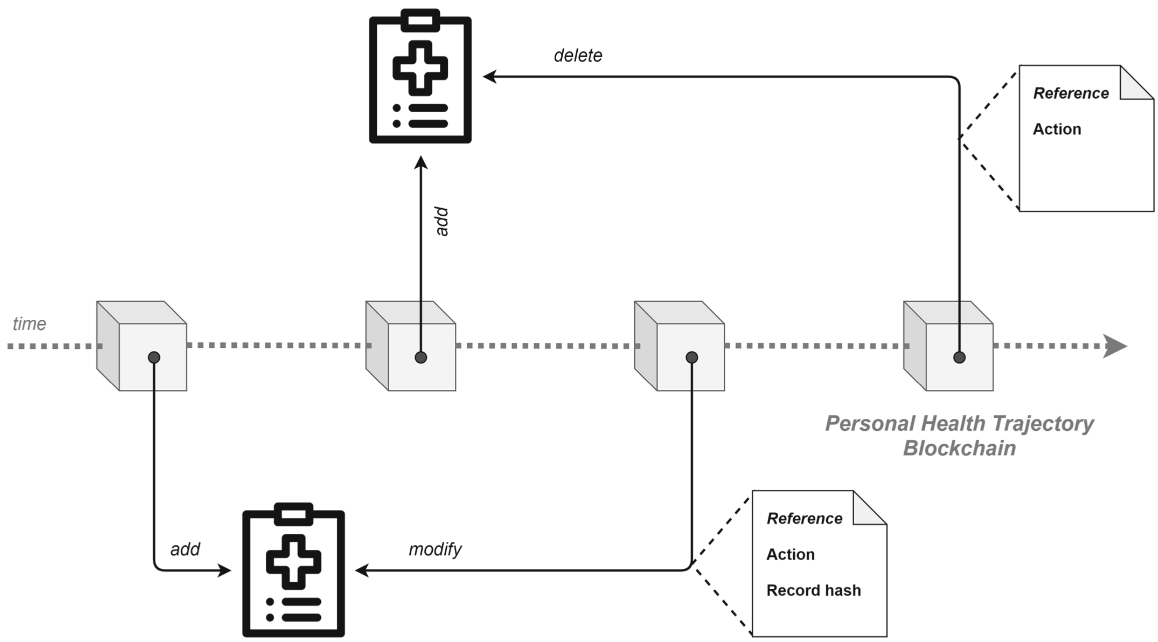


Fig. 2. Blockchain-based registry for Personal Health Trajectory

Blockchain as a technology to perform traceability on the Personal Health Trajectory allows the generation of a blockchain with the changes in the patient's health records. In this way, each block is associated with a CRUD operation on one of the patient's records—see Fig. 2. So, those records that do not have any associated block in the chain may be treated as data from untrusted sources, as discussed above. For records with blocks that store transactions on them, all the advantages discussed in the previous section can be applied.

In addition, the fact of using blockchain to obtain traceability over the Personal Health Trajectory allows not only to obtain the advantages already mentioned in the previous section, but also offers another series of extra advantages. For example, saving in the Personal Health Trajectory the status of a record when it is referenced from a block is more secure with blockchain. If the status of a record is obtained by calculating a hash associated with the content of the record, this hash should be stored in the block of the operation on the record. This block has the advantages of being stored in a blockchain, such as being part of an immutable chain, protected by a hash associated with the content of the block that does not allow anyone to change the content of the block without breaking and invalidating the chain—this is one of the security principles of blockchain. Therefore, it could be said that the integrity of the content of the record is guaranteed by the use of a double-hash. If someone were to maliciously attempt to alter the contents of the record, the hash associated with its contents, stored in the last block of a write operation on the blockchain record, would have to be rewritten. If someone tried to do this, it would invalidate the blockchain chain and the attack would be detected.

On the other hand, blockchain technology already offers advanced mechanisms to secure other aspects such as who accesses a blockchain and the permissions they have over it, among others. Therefore, every interaction that takes place in the Personal Health Trajectory is recorded by the blockchain technology itself. In this way, it can be controlled who registers each record—by knowing who and when generates the block—or who accesses this blockchain to register and visualize changes in traceability—even formalizing procedures through smart contracts.

Figure 3 shows what a base architecture that uses blockchain to integrate distributed stored data would look like if it is extended to maintain traceability of records. As can be seen, the records are stored outside the blockchain and only a reference to them is stored from the blockchain. To perform traceability, along with the reference to the record—which can be stored with any type of attribute, as is done in this case with the attributes *URL Resource* and *Key resource*—, new attributes are stored such as the action on the record that is represented by that block and the hash of the record content—in case of a write operation, as a *create* or *modify* operation.

The data that may be referenced, as in many data integration proposals, is data generated by healthcare institutions or data generated by IoMT or WoMT devices.

Similarly, it can be seen how the user's smartphone maintains a copy of the blockchain that it integrates and provides traceability over its Personal Health Trajectory. However, this blockchain can be shared with institutions for them to read or write to their Personal Health Trajectory, maintaining the integration and traceability of records at all times. How this sharing is done is more dependent on the data integration proposal than on this proposal on traceability.

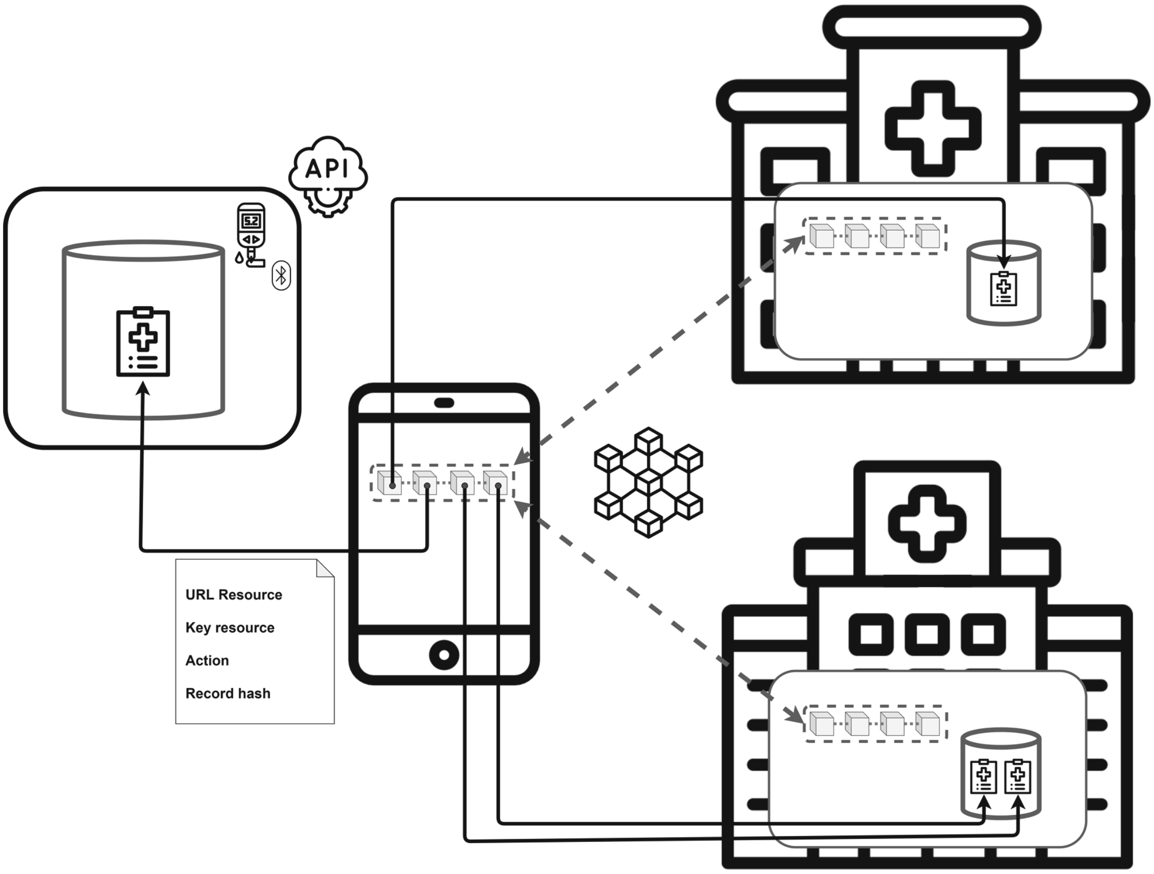


Fig. 3. Blockchain registry working on records from institutions and IoT services

Some proposals perform this step through the user, who shares a key for institutions to access their blockchain. Other proposals, such as that of the authors of this paper, seek more complex mechanisms, such as blockchains' federation [18], but which allow verified institutions associated with a data-sharing program to access the data of any of the verified institutions without the user's explicit consent for each access–something interesting for treating emergency patients, for example.

To finish, from the above it is intuited that creating such a proposal implies the use of private blockchains with permissions, where it is controlled who can read and generate new blocks in the blockchain of each user.

5 Discussion

As it has been manifested during all the manuscripts, the advantages of having a health registry that maintains the traceability of health records are clear. The achievement of this registry is closely linked to the existence of health data integration proposals. Despite this, the usage of other different structures to obtain this registry could be proposed, having a structure that maintains data integration and another one that maintains data traceability. However, to have real traceability of a patient's health, the need to having a global vision of all patient's health data becomes necessary. If no data integration structure is taken into account as starting point to access this global vision, the data integration's task must be replayed once again by new proposals to obtain the traceability structure.

Even being convinced that the obtaining of health traceability is an extension of health data integration proposals, the details about how to obtain it are not free of discussion, since different topics emerge around it.

The clearest example is about if real traceability can be provided only by maintaining the last version of records in the health system, or if it is become necessary to have stored—and referenced in the different blocks about a record—the different versions of a record across the time—at least until the record is solicited to be deleted—if done. In the proposal presented, it is known that various blocks reference the same record because their pointers refer to the same point. If different versions of a record become to be stored, each of the pointers referring to the same record will have references to different points. So, the inclusion of a common identifier to all records being versions of a unique real record is necessary. Taking as a premise that all the versions of a record are generated by the same institution—something that has so much sense—makes easier the task of managing the identifier of records.

In addition, another topic to be discussed is how the patient—being the real owner of this data structure—grant access to her health registry to institutions and IoT services to begin writing and/or read on it. In the case of IoT services, a possible solution is that patient's smartphone—having a copy of the registry—perform the writing tasks associated with records of IoT devices. However, in the case of health institutions, this is not so simple. The health professionals must access the registry not only for writing but also to read on it when the patient is under treatment. How to achieve this is discussed by several proposals on data integration, and their solutions can be applied in this case also—since on our approach architecture under data integration is the same under data traceability. Some issues arise around this, such as how access is granted in case of emergency if the user is the one granting it. In this sense, the authors of this paper are already working on solving problems of this type with other proposals such as the blockchain federation [18]. With all this, it is still up in the air that access to all patient health data traceability, and not only to their integrated data, will be given to them.

6 Conclusions and Future Work

This paper has discussed how distributed health data integration processes can be improved and taken into account to provide traceability of patient health data—as is already done in other fields. Specifically, the concept of Personal Health Trajectory—on which the authors of this paper have worked—has been presented and it has been shown how it can be extended to guarantee traceability.

Finally, efforts have been focused on showing a more pragmatic proposal—although without reaching its implementation—of how the traceability of the

Personal Health Trajectory could be achieved by implementing the latter as a registry of changes of the patient's health reality in blockchain. Different security mechanisms have been proposed around this registry, which takes advantage of the traceability offered to achieve levels of security that mere data integration does not achieve.

However, this proposal have already work to do. What is proposed here is to highlight the need for this traceability and its relationship with existing data integration proposals. There is still work ahead in terms of its implementation and the inclusion of new security techniques around the blockchain registry—some of which are already mentioned in the discussion, such as the use of smart contracts.

Acknowledgments. This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), the FPU19/03965 grant, the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and the European Regional Development Fund.

References

1. Chen, L., Lee, W.K., Chang, C.C., Choo, K.K.R., Zhang, N.: Blockchain based searchable encryption for electronic health record sharing. Future Gener. Comput. Syst. **95**, 420–429 (2019). https://doi.org/10.1016/J.FUTURE.2019.01.018
2. Dubovitskaya, A., et al.: Intelligent health care data management using blockchain: current limitation and future research agenda. In: Gadepally, V., et al. (eds.) DMAH/Poly - 2019. LNCS, vol. 11721, pp. 277–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-33752-0_20
3. Feng, H., Wang, X., Duan, Y., Zhang, J., Zhang, X.: Applying blockchain technology to improve agri-food traceability: a review of development methods, benefits and challenges. J. Clean. Prod. **260**, 121031 (2020)
4. Flores-Martin, D., Rojo, J., Moguel, E., Berrocal, J., Murillo, J.M.: Smart nursing homes: self-management architecture based on iot and machine learning for rural areas. Wirel. Communi. Mob. Comput. **2021** (2021)
5. Galvez, J.F., Mejuto, J.C., Simal-Gandara, J.: Future challenges on the use of blockchain for food traceability analysis. TrAC Trends Anal. Chem. **107**, 222–232 (2018)
6. Gatouillat, A., Badr, Y., Massot, B., Sejdic, E.: Internet of medical things: a review of recent contributions dealing with cyber-physical systems in medicine. IEEE Internet Things J. **5**(5), 3810–3822 (2018). https://doi.org/10.1109/JIOT.2018.2849014
7. Gong, J., Lin, S., Li, J.: Research on personal health data provenance and right confirmation with smart contract. In: 2019 IEEE 4th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), vol. 1, pp. 1211–1216. IEEE (2019)
8. Helal, S., Jain, R.: Digital health-active and healthy living. Computer **52**(11), 14–17 (2019)
9. Henly, S.J., Wyman, J.F., Gaugler, J.E.: Health trajectory research: a call to action for nursing science. Nurs. Res. **60**(3 SUPPL.) (2011). https://doi.org/10.1097/NNR.0b013e31821cc240

10. Jalali, L., Huo, D., Oh, H., Tang, M., Pongpaichet, S., Jain, R.: Personicle: personal chronicle of life events. In: Workshop on Personal Data Analytics in the Internet of Things (PDA@ IOT) at the 40th International Conference on Very Large Databases (VLDB), Hangzhou, China (2014)
11. Kalra, D.: Electronic health record standards (2006)
12. Kassab, M., Defranco, J., Malas, T., Graciano Neto, V.V., Destefanis, G.: Blockchain: a panacea for electronic health records? In: Proceedings - 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare, SEH 2019, pp. 21–24. Institute of Electrical and Electronics Engineers Inc., May 2019
13. Kyazze, M., Wesson, J., Naude, K.: The design and implementation of a ubiquitous personal health record system for South Africa. Stud. Health Technol. Inform. **206**, 29 (2014)
14. Li, H., Zhu, L., Shen, M., Gao, F., Tao, X., Liu, S.: Blockchain-based data preservation system for medical data. J. Med. Syst. **42**(8), 1–13 (2018). https://doi.org/10.1007/S10916-018-0997-3
15. Philip, N., et al.: Design of a restful middleware to enable a web of medical things. In: 2014 MOBIHEALTH, pp. 361–364, November 2014. https://doi.org/10.1109/MOBIHEALTH.2014.7015986
16. Roehrs, A., Da Costa, C.A., da Rosa Righi, R., De Oliveira, K.S.F.: Personal health records: a systematic literature review. J. Med. Internet Res. **19**(1), e13 (2017). https://doi.org/10.2196/jmir.5876, http://www.jmir.org/2017/1/e13/
17. Roehrs, A., da Costa, C.A., da Rosa Righi, R.: OmniPHR: a distributed architecture model to integrate personal health records. J. Biomed. Inform. **71**, 70–81 (2017). https://doi.org/10.1016/j.jbi.2017.05.012
18. Rojo, J., Hernandez, J., Murillo, J.M., Garcia-Alonso, J.: Blockchains' federation for integrating distributed health data using a patient-centered approach. In: 2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH), vol. 1, pp. 52–59. IEEE Computer Society, Los Alamitos, June 2021. https://doi.org/10.1109/SEH52539.2021.00016, https://doi.ieeecomputersociety.org/10.1109/SEH52539.2021.00016
19. Rojo, J., Flores-Martin, D., Garcia-Alonso, J., Murillo, J.M., Berrocal, J.: Automating the interactions among IoT devices using neural networks. In: 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), pp. 1–6. IEEE (2020)
20. Rojo, J., Hernandez, J., Murillo, J.M.: A personal health trajectory API: addressing problems in health institution-oriented systems. In: Bielikova, M., Mikkonen, T., Pautasso, C. (eds.) ICWE 2020. LNCS, vol. 12128, pp. 519–524. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-50578-3_37
21. Rojo, J., Moguel, E., Fonseca, C., Lopes, M., Garcia-Alonso, J., Hernandez, J.: Time series forecasting to predict the evolution of the functional profile of the elderly persons. In: García-Alonso, J., Fonseca, C. (eds.) IWoG 2020. LNB, pp. 11–22. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-72567-9_2
22. Helou, S., Abou-Khalil, V., El Helou, E., Kiyono, K.: Factors related to personal health data sharing: data usefulness, sensitivity and anonymity. Stud. Health Technol. Inform. **281**, 1051–1055 (2021). https://doi.org/10.3233/SHTI210345, https://pubmed.ncbi.nlm.nih.gov/34042839/
23. Spil, T., Klein, R.: Personal health records success; why google health failed and what does that mean for Microsoft HealthVault? In: Proceedings of the Annual Hawaii International Conference on System Sciences, pp. 2818–2827. IEEE Computer Society (2014). https://doi.org/10.1109/HICSS.2014.353

24. Zhang, Y., Qiu, M., Tsai, C.W., Hassan, M., Alamri, A.: Health-CPS: healthcare cyber-physical system assisted by cloud and big data. IEEE Syst. J. **11**, 1–8 (2015). https://doi.org/10.1109/JSYST.2015.2460747
25. Zhang, Y., Li, J., Zheng, D., Chen, X., Li, H.: Towards privacy protection and malicious behavior traceability in smart health. Pers. Ubiquit. Comput. **21**(5), 815–830 (2017). https://doi.org/10.1007/s00779-017-1047-8

Appendix L

Social Events Analyzer (SEA): A Toolkit for Mining Social Workflows by Means of Federated Process Mining

Authors: *Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal.*

Publication type: *Conference paper (Demo track).*

Conference: *International Conference on Web Engineering.*

Year of publication: *2022.*

DOI: *10.1007/978-3-031-09917-5_39*

2021 GGS Class (Rating): *3 (B-).*

Social Events Analyzer (SEA): A Toolkit for Mining Social Workflows by Means of Federated Process Mining

Javier Rojo[1(✉)], José García-Alonso[1], Javier Berrocal[1], Juan Hernández[1], Juan M. Murillo[1], and Carlos Canal[2]

[1] University of Extremadura, Caceres, Spain
{javirojo,jgaralo,jberolm,juanher,juanmamu}@unex.es
[2] Universidad de Málaga, Málaga, Spain
canal@lcc.uma.es

Abstract. Users' smartphones collect information about the different interactions they perform in their daily life, including web interactions. Mining this information to discover user's processes provides information about them as individuals and as part of a social group. However, analyzing events produced by human behavior, where indeterminism and variability prevail, is a complex task. Techniques such as process mining focus on analyzing customary event logs produced by a system where all the possible interactions are predefined. The analysis become even harder when it involves a group of people whose joint activity is considered part of a Social Workflow. In this demo we present Social Events Analyzer (SEA), a toolkit for easy Social Workflow analysis using a technique called Federated Process Mining. The tool offers models more faithful to the behavior of the users that make up a Social Workflow and opens the door to the use of process mining as a basis for the creation of new automatic procedures adapted to the user behavior.

Keywords: Process mining · Pattern discovery · Social workflows · Federated process mining

1 Introduction

Smartphones constantly collect information about their user's daily actions [7], including the interactions users perform with web pages [6]. These actions can be considered as the events of a process modeling the user's behaviour. This allows techniques such as process mining to analyze this process at the individual level, but also considering the users as part of a group with similar behaviour's processes or Social Workflows (SOW) [3].

However, current process mining techniques are designed to mine information obtained from well-defined processes. Human behavior represented in Social Workflows is usually not deterministic, but highly variable [3]. So, analyzing this kind of information becomes a problem for process mining. Even more at the

T. Di Noia et al. (Eds.): ICWE 2022, LNCS 13362, pp. 477–480, 2022.
https://doi.org/10.1007/978-3-031-09917-5_39

societal level, where indeterminism from different users is aggregated—obtaining processes that do not provide real knowledge about any of the users or about the group itself.

Current techniques such as clustering [4] try to solve this problem, grouping users in not previously-known clusters according their behaviour. Nevertheless, they do not focus on mining a concrete Social Workflow, but on mining all users data, not knowing *a priori* behavioural patterns of interest to be met by users that are going to be analyzed.

In order to offer an alternative in these situations, Social Events Analyzer (SEA) has been developed. This tool allows to perform a first phase of individual mining in each user's smartphone to filter those users and traces that meet a concrete, looked for, behaviour. In this way, only users with common behavioural patterns are considered part of the social group to be analyzed later. The premise on which this tool is based is that human behaviour is not erratic per se [2]. So, individually analyzing each user's behaviour before integrating it improve the representation of each user in the Social Workflow and the one of the users' group consequently.

Thanks to this tool, processes that could not be analyzed otherwise due to heterogeneity in users interactions, can now be analyzed. As well, some additional benefits come from filtering data on smartphones: reduction of the amount of data sent to server —reducing the energy footprint [1]—, and reduction of the computational load on server.

Moreover, SEA allows the development of automatic systems using processes' information to make recommendations or personalize processes itself. Complementing this manuscript, the use of SEA on a WoT/IoT use case is shown[1].

2 Social Events Analyzer (SEA)

Social Events Analyzer (SEA) is based on the novel Federated Process Mining concept. It offers the necessary tools to carry out process mining on Social Workflows by means of Federated Process Mining, where process mining is performed on two phases: an individual first one on users' smartphones, generating an individual model in order to filter users that are going to belong to a concrete Social Workflow; and a second one on a server, generating social processes with data resulting from filtering in the first phase. Since the interesting behaviour's pattern —or patterns— to be meet by users is known a priori, filtering is performed by means of a query where this behaviour is represented. For example, the query may ask for users who have ended up watching economic news videos on YouTube when they started watching videos about the COVID-19 pandemic. For users meeting the pattern sought in their individual models, traces are checked one by one, sending to the server only those that contains the pattern. In this way, traces are only checked when the behaviour is enclosed in the model and it is known that the user meet the searched behavior —this results in greater

[1] https://youtu.be/d2tOYWWhYC0.

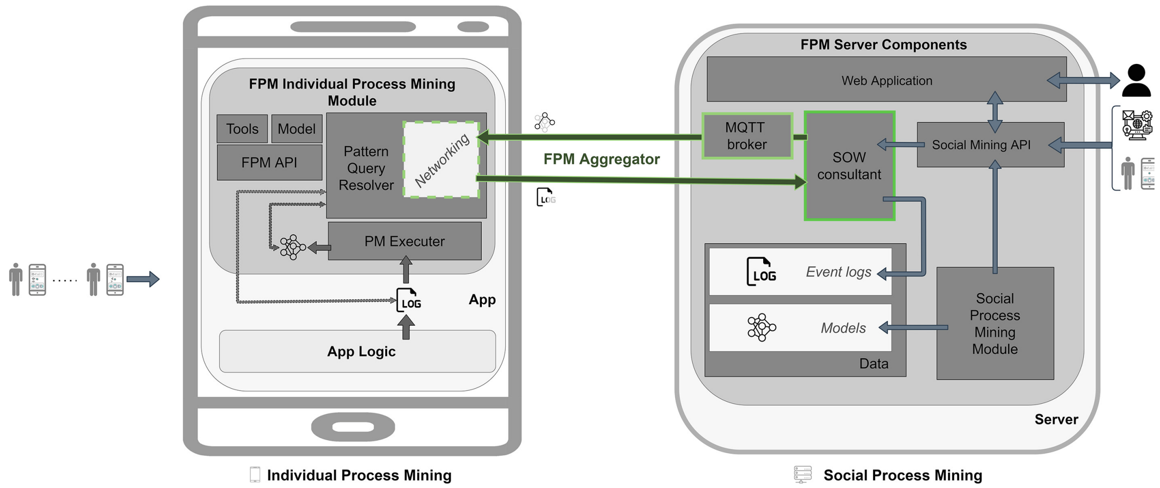


Fig. 1. SEA's architecture.

efficiency when many queries are made or when the amount of traces to be stored is very large.

Social Events Analyzer —Fig. 1— offers a concrete implementation of Federated Process Mining in the way of a series of components that must be included in the application that generates the data and a complete Federated Process Mining server. The three main components, that are divided into a number of sub-components, are:

Individual Process Mining component[2]**.** This component is the one deployed on smartphones. At the moment it is only available on Android devices. Specifically, SEA offers the *FPM Individual Process Mining module*, which must be included in the mobile application that generates the event log —in .XES format— to be mined. The generation of this event log must be addressed by developers of the application—using information collected in the app logic.

Social Process Mining Component[3]**.** This component is the one that is deployed on the server. It is actually a set of web services—implemented in Python—and a web application—in Typescript—that work together. Each of them is in charge of part of the functions to be performed by the Social Process Mining component, highlighting the Social Mining API. It is a REST API that works as an access point to the Social Workflows information, offering data and operations to manage it to the Web Application, to third-parties or even to the users' smartphones themselves when these are the ones interested in accessing the data of a given Social Workflow.

FPM Aggregator. This component has been implemented as part of the previous ones —mark in green color in Fig. 1—, using previous works on the deployment of APIs in mobile devices [5]. It is employed to enable communication between individual and social parties—being used to send queries from *Social*

[2] https://bitbucket.org/spilab/individualpmmodule.
[3] https://bitbucket.org/spilab/fpmserver.

Mining component to the smartphones in Linear Temporal Logic (LTL) format and to send traces from these as response to queries.

3 Conclusion and Future Work

SEA makes use of the concept of Federated Process Mining to enable the usage of process mining on Social Workflows. For this purpose, it offers a complete toolkit with the necessary components to be included in smartphones and the server where social mining is going to be performed. As result, models more faithful to the members of a social group and the optimization of resources needed to perform process mining are achieved. In addition, SEA brings the arrival of a new generation of automatic systems based on user process information.

Acknowledgments. This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014–2020), RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), and UMA18-FEDERJA-180 (Junta de Andalucía/ATech/FEDER), by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), by the FPU19/03965 grant and by the European Regional Development Fund.

References

1. Berrocal, J., et al.: Early evaluation of mobile applications' resource consumption and operating costs. IEEE Access **8**, 146648–146665 (2020). https://doi.org/10.1109/ACCESS.2020.3015082
2. Gonzalez, M.C., Hidalgo, C.A., Barabasi, A.L.: Understanding individual human mobility patterns. Nature **453**(7196), 779–782 (2008). https://doi.org/10.1038/nature06958
3. Görg, S., Bergmann, R.: Social workflows - vision and potential study. Inf. Syst. **50**, 1–19 (2015). https://doi.org/10.1016/j.is.2014.12.007
4. Jablonski, S., Röglinger, M., Schönig, S., Wyrtki, K.M.: Multi-perspective clustering of process execution traces. EMISAJ Int. J. Concept. Model. **14**(2), 1–22 (2019). https://doi.org/10.18417/emisa.14.2
5. Laso, S., Linaje, M., Garcia-Alonso, J., Murillo, J.M., Berrocal, J.: Artifact abstract: deployment of apis on android mobile devices and microcontrollers. In: 2020 IEEE International Conference on Pervasive Computing and Communications (PerCom), pp. 1–2 (2020). https://doi.org/10.1109/PerCom45495.2020.9127353
6. Poggi, N., Muthusamy, V., Carrera, D., Khalaf, R.: Business process mining from e-commerce web logs. In: Daniel, F., Wang, J., Weber, B. (eds.) BPM 2013. LNCS, vol. 8094, pp. 65–80. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-40176-3_7
7. Rojo, J., Flores-Martin, D., Garcia-Alonso, J., Murillo, J.M., Berrocal, J.: Automating the interactions among iot devices using neural networks. In: 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), pp. 1–6 (2020). https://doi.org/10.1109/PerComWorkshops48775.2020.9156111

Appendix M

Quantum service-oriented computing: current landscape and challenges

Authors: *Enrique Moguel, Javier Rojo, David Valencia, Javier Berrocal, Jose Garcia-Alonso, Juan M Murillo.*

Publication type: *Journal article.*

Journal: *Software Quality Journal.*

Year of publication: *2022.*

DOI: *10.1007/s11219-022-09589-y*

2021 JCR IF (Rank): *1.813 (Q3 69/110)*

Software Quality Journal
https://doi.org/10.1007/s11219-022-09589-y

Quantum service-oriented computing: current landscape and challenges

Enrique Moguel[1] · **Javier Rojo**[1] · **David Valencia**[1] · **Javier Berrocal**[1] · **Jose Garcia-Alonso**[1] · **Juan M. Murillo**[1]

Accepted: 20 March 2022

Abstract
The development that quantum computing technologies are achieving is beginning to attract the interest of companies that could potentially be users of quantum software. Thus, it is perfectly feasible that during the next few years hybrid systems will start to appear integrating both the classical software systems of companies and new quantum ones providing solutions to problems that still remain unmanageable today. A natural way to support such integration is Service-Oriented Computing. While conceptually the invocation of a quantum software service is similar to that of a classical one, technically there are many differences and technological limitations, which refer to platform independence, decoupling, scalability, etc. To highlight these differences and the difficulties to develop quality quantum services, this paper takes a well-known problem to which a quantum solution can be provided, integer factorization, making use of the Amazon Braket quantum service platform. The exercise of trying to provide the factorization as a quantum service is carried out following the best practices, design patterns and standards existing in the implementation of classical services. This case study is used to highlight the rough edges and limitations that arise in the integration of classical-quantum hybrid systems using service-oriented computing. The conclusion of the study allows us to point out directions in which to focus research efforts in order to achieve effective quantum service-oriented computing.

Keywords Quantum services · Classical services · Hybrid classical-quantum software · Quality

1 Introduction

Quantum computing is starting to establish itself as a commercial reality (MacQuarrie et al., 2020). Several major computing corporations have already built working quantum computers, there are tens of quantum programming languages and simulators, and real quantum computers can already be used by the general public through the cloud. All this is motivating software development companies to take the first steps by launching their own

✉ Enrique Moguel
enrique@unex.es

Extended author information available on the last page of the article

proposals for the integral development of quantum software (Pérez-Castillo & Piattini, 2020; Wille et al., 2019; Bergholm et al., 2018; Piattini et al., 2021; Pérez-Castillo et al., 2021). All of these signals are an urgent call to software engineers to prepare and enroll to sail the quantum seas.

It is generally assumed that on the way to a new world in which software systems are mostly quantum, there will be a transition time in which classical and quantum systems must not only coexist but collaborate by interacting with each other (Sodhi, 2018). This is what has been called classical-quantum hybrid systems (McCaskey et al., 2018, 2020). The advances provided by software engineering in the last two decades allow us to affirm that a natural way to approach such collaborative coexistence is by following the principles of service engineering and service computing.

Among the reasons for this, two can be highlighted. On the one hand, as hardware technology matures and achieves more affordable costs, it is reasonable to think that companies will be inclined to use quantum infrastructure and quantum software as a service, as they are used to do nowadays with classical computing resources. This has already happened with classical computing services, companies such as Amazon, Microsoft, IBM, and Google that have started approaching the world of quantum computing Digital Journal (2022). And it is not unreasonable to think that these same companies will offer both classical and quantum computing services indiscriminately.

On the other hand, it is reasonable to think that at least initially, quantum systems will be used to solve only those parts of problems that cannot be solved by classical architectures, while those parts of problems that are already efficiently solved by classical architectures will continue to be treated as before. For example, in the field of health, it will be possible to accelerate the discovery of new medicines, perform simulations of molecules for pharmaceuticals, and enable the development of new medicines easier and faster (Zinner et al., 2022); in the financial domain, it could help analyze all possible scenarios and compare risks and optimize a financial portfolio Pistoia et al. (2021); it could also help us decrypt cryptographic security systems, optimize travel routes and logistics, model climate change, etc. (Cheng et al., 2021).

A natural way to achieve these quantum solutions is by consuming quantum services.

Conceptually, the invocation of a quantum program is similar to that of a classical service. A piece of software needs a result to be produced by a quantum system and to do so it consumes a service. For the sake of service engineering principles, such an invocation should even be agnostic of whether the service that will return the result is quantum or not. Technically, however, the invocation of a quantum service is very different from that of classical service and still poses a challenge today. This is due to the inherent nature of quantum computing, meaning that a quantum service differs from classical services in which it includes entanglement and superposition of solutions, and will collapse to a single solution when interacting with the external world, leading to having a probability amplitude associated to the results obtained upon observations of the quantum system.

Servitizing a quantum piece of software, namely converting it into a service endpoint that can be invoked through a standard service request, is possible with the existing technology. However, in the current status of quantum software, it means eliminating most of the advantages that made service-oriented computing a commercial success, especially, those related to software quality like composability, modularity, maintainability, reusability, etc. (Ravichandran & Rai, 2000).

The reasons for this are multiple. First and foremost, the specificity of each architecture makes quantum algorithms and their parameters dependent on the specific quantum hardware in which they will be executed. But also, the return of the result of a quantum process is subject to errors or does not support the intermediate verification of results (due to the system collapse). Thus, different quantum architectures require very different skillsets. For example, circuit-based quantum programming requires developers to know the details of quantum gates (Wille et al., 2019), while quantum annealing programming requires adapting the problem to that specific metaheuristic (Boixo et al., 2013). Consequently, invoking a quantum program in an agnostic way is impossible today and violates all the principles of service engineering. All of the above highlights the need for the development of Quantum Service Engineering (Piattini et al., 2020).

In this paper, we explore the current state of quantum software engineering from a service-oriented point of view. The integer factorization problem (Nielsen & Chuang, 2002; Jiang et al., 2018) is used to illustrate the different problems that arise when a quantum piece of code is tried to be used as a service. Amazon Braket[1], the quantum computing service offered by Amazon as part of their AWS suite, is used as the services platform. Amazon is globally recognized as the leader company in services technology, and through Braket, they offer access to quantum computers from three different hardware providers. Using this platform as the basis for quantum services development, we identify the problems and limitations of current technology using the lessons learned from service-oriented computing. The paper provides an exploration of the problems to be addressed pointing out different research directions for the development of a future quantum service engineering.

In order to do that the rest of the paper is organized as follows. Section 2 details this work background in both fields of service-oriented computing and quantum software development. Section 3 describes one of the possible ways to implement a classic service following best practices, design patterns, and existing standards. Section 4 addresses the servitization of quantum software using Amazon Braket. Section 5 lists the main limitations found in today technology that limits the benefits of quantum services. And finally, Sect. 6 presents the paper conclusion and future works.

2 Background

Service-oriented computing is a paradigm that utilizes services as the fundamental elements for developing software (Papazoglou, 2003). One of its pillars is service-oriented architecture (SOA) that proposes the implementation of complex software solutions through the use of a set of services that are composed and choreographed (Endrei et al., 2004). The basic composition mechanism is the service call that allows a service to be invoked from another piece of code (potentially another service) agnostically with respect to the place, technology, or architecture of the invoked service. The services can thus be maintained, evolved, replaced, and reused independently without affecting the software that invokes them. It is precisely these properties that make them especially attractive to create quality software. Over the last two decades, service-oriented computing and SOA in general, and web services in particular, have been at the center of intense research (Bouguettaya et al., 2017) leading to monolithic software being gradually replaced by service-based software run in the cloud (Mazlami et al., 2017; Haugeland et al., 2021).

The success of service-oriented computing has been possible, to a great extent, thanks to the development of cloud computing as a paradigm that aims to provide reliable and

[1] https://aws.amazon.com/braket/

customized dynamic computing environments (Wang et al., 2010). Some of the main reasons behind the success of the cloud include: the ability for companies to better control their costs since they do not have to buy, upgrade and maintain expensive hardware and only pay for their use; and the flexibility and scalability provided by cloud vendors that allow companies to instantly increase or decrease their hardware capabilities according to their needs. These have made the cloud one of the most successful business models of the last decades. Recent estimations calculate that in the USA only, cloud computing contributed approximately 214 billion dollars in value-added to the GDP and 2.15 million jobs in 2017 Hooton (2019).

Given these numbers are not a surprise that current quantum computers, which are still very expensive hardware to build and operate, are being offered following this model. In its current form, most quantum computers can be accessed through the cloud in a model called by some researchers quantum computing as a service (QCaaS) (Rahaman & Islam, 2015). This model can be compared to the classical Infrastructure as a service (IaaS) model offered in cloud computing. QCaaS allows developers to access some of the world's existing quantum computers; nevertheless, this access is very dependent on the specific hardware and developers must have great proficiency in Quantum Computing to benefit from its advantages.

To increase the abstraction level of QCaaS, there are multiple ongoing research efforts. From a commercial perspective, platforms like the above-mentioned Amazon Braket provide a development environment for quantum software engineers or, like QPath[2], an ecosystem that covers a wide range of possible applications by integrating the software classical and quantum worlds in a quantum development and application life cycle platform for high-quality quantum software.

From a more academic perspective, a significant number of works are starting to appear in the field of quantum software engineering (Zhao, 2020; Piattini et al., 2020). These works focus on translating the lessons learned in classical software engineering to improve the quality of quantum software. However, as far as the authors know, very few works focus on the perspective of service engineering for quantum and hybrid software.

However, some works are starting to appear in this domain, like Barzen et al. (2021) where quantum application as a service (QaaS) is proposed to narrow the gap between classical service engineering and quantum software. Works like this reveal the need to focus on a service-oriented approach for the development of quantum services.

3 A good classic service implementation

Before starting to discuss the proposed case study and the limitations found, we will describe one of the possible ways to manage the entire life-cycle of a classic service, starting with the implementation, followed by its deployment and its subsequent monitoring and maintenance. For this purpose, we will follow existing best practices, design patterns, and standards.

Figure 1 shows how a good classical version of the implementation, deployment, and maintenance of a service could look like. We would like to point out that there is no single best way to define a classic service and that it can be developed following different

[2] https://www.quantumpath.es/

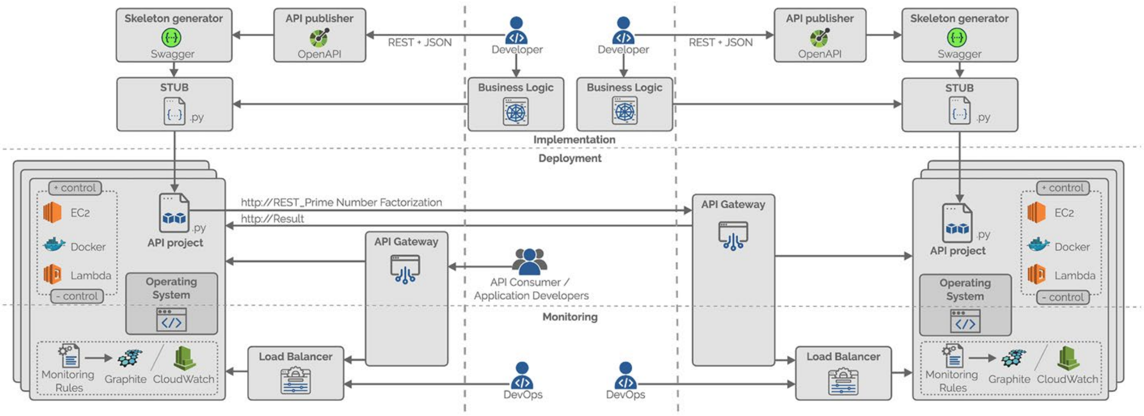


Fig. 1 A good classic version of a implementation of a service

approaches. However, we have tried to follow some of the most accepted best practices, design patterns, and standards that have become very relevant in recent years for the definition and development of classical services. Among them, we followed the models defined by Newman (2021) (one of the early pioneers of microservice architecture), the microservices design patterns of Richardson (2019) (a renowned and well-respected microservices expert), and the guide of Wolff (2019) (a renowned software architect who has written several books on microservices).

In this regard, Fig. 1 is split vertically in two. On the left side can be seen the service client (which can be a service itself). In the case study, which will be detailed in Sect. 4, this would be the cryptographic decryption service. And on the right side, the invoked service can be seen, in the commented case study, it would be the algorithm for calculating the factorization of integers.

Horizontally, the same Fig. 1 is split into three layers that represent different phases in the service life cycle. On the top, the implementation phase of the service can be seen, where the service is developed. In the middle, the deployment phase of the service can be seen, where it is published so that it can be invoked. And at the bottom, the monitoring phase can be seen where the service is being used. For each of these phases, some of the most relevant standards and best practices in classic services will be discussed.

For the implementation of a classical service, a developer needs to combine two main aspects. The business logic of the service, which is specific to each service and implemented ad hoc, and the service API. For the definition of the service API, the OpenAPI[3] specification can be used. This specification defines a standard, language-agnostic interface to RESTful APIs which allows both humans and computers to discover and understand the capabilities of the service without access to source code, documentation, or through network traffic inspection. An OpenAPI definition can then be used by code generation tools like Swagger to generate servers and clients in various programming languages. Using OpenAPI, for our case study, the integer factorization service can be defined with its input and output parameters. From this definition, a code stub can be generated, for example in Python, in which the business logic of the service can be added. By following this approach, the service could be accessed using a REST request and JSON to provide the input parameters.

[3] https://www.openapis.org/

Once the service is implemented, it must be deployed so clients can access it. For this deployment, in most cases, a cloud computing solution is used in which we deploy our API project in hardware provided by a third party. Depending on the level of control, we require over the hardware, there are several alternatives ranging from IaaS solutions, like Amazon Elastic Cloud Computing (EC2)[4], where we have complete control over a virtual machine, to the use of containers like Docker[5] or to serverless approaches like Amazon Lambda[6], where no control over the underlying infrastructure is provided to the service creators. Independently of the deployment approach followed the proposed service will have some coupling with the operating system in which it is deployed.

At the same level, one of the most used design patterns in the deployment of classical services is the API Gateway. To put it simply, the API Gateway takes all API requests from a client, determines which services are needed, and combines them into a unified, seamless experience for the user. For the proposed case study, the service would invoke the prime number factorization service through the API Gateway of the back-end. The API Gateway would transmit the petition to the appropriate service and provide the response once it has been computed.

Finally, once the service is deployed and is being invoked by users it must be monitored by the DevOps team to ensure that the service can deal with the demand. To address this, usually, a Load Balancer can be used in combination with the API Gateway. Additionally, monitoring rules can be defined in combination with tools like Graphite[7] or CloudWatch[8] to obtain fine-grained information of the service status. This would allow us to control the status of the prime number factorization service, the number of requests, how much are we going to pay for the infrastructure at the end of the month, etc.

As can be seen, even for a “simple” service like the prime number factorization service the development, deployment, and monitoring process are quite complex. It could be thought that most of the components in Fig. 1 are not really necessary for a simple service. However, all of them are there for a reason. Service-oriented computing has adopted these patterns and good practices because all of them contribute to the benefits provided by service orientation. The most relevant of these benefits are:

- **Platform independence.** By using a REST API, which in turn is based on HTTP, IP, and the rest of internet protocols, services can be invoked from any platform independently of the language of the service, the language of the client, and the platforms in which both are run. Similarly, by using JSON, data can be transferred between services regardless of the implementation languages. Finally, by using the OpenAPI specification, an independent, well-formed API will be defined that can be easily consumed by any client.
- **Location independence.** Classical services are also independent of the location in which they are deployed. This independence can be considered at two levels:

4 https://aws.amazon.com/ec2
5 https://www.docker.com/
6 https://aws.amazon.com/lambda
7 https://graphiteapp.org/
8 https://aws.amazon.com/cloudwatch

  - *Physical independence.* This is provided by REST, HTTP, and DNS which allow service developers to use a URL to access a service independent of where it is deployed.
  - *Logical independence.* Meaning the independence of a given service inside a more complex project is provided by an API Gateway that hides this complexity from the service clients.

- **Decoupling.** Three different types of decoupling must be taken into account:

  - *Decoupling between services.* The decoupling between different services of a single API is provided by the API Gateway which can communicate services without the services knowing each other.
  - *Decoupling between services and hardware.* The decoupling between services and hardware and operating systems is provided by the platform in which the services are deployed (EC2, Docker, Lambda, etc.).
  - *Decoupling between services and programming language.* The decoupling between the services and the programming language in which they are written is provided by the OpenAPI Specification and code generation tools that are able to generate the service stub in different programming languages.

- **Scalability.** Services are also resilient and developers are able to scale to address changes in the demand. The most common way to provide this scalability, without incurring high economic costs from the cloud provider, is the use of elastic platforms and a load balancer that is able to start and stop new instances of the service as needed.
- **Composability.** Services also have to be composable, so a set of simple services can be composed to provide solutions to complex problems. This composability can be provided by the API Gateway that can decompose a single invocation into calls to different services without the services knowledge.
- **Reliability.** Services have to be reliable in the broadest sense of the word, including security, maintainability, accountability, and many other X-abilities. To achieve this, a complete set of monitoring and analytic tools are needed that provide all the information needed about the services.

To achieve all these benefits a complex infrastructure, like the one shown in Fig. 1, is needed. However, as far as the authors know, there is no support to obtain the benefits of service-oriented computing if one of the services of an API is implemented as a quantum service.

4 Quantum servitization

There are some problems that cannot be solved efficiently using classical computation, and a clear example is that of factoring prime numbers. This is where quantum computing can offer the greatest benefits. But without forgetting all the knowledge acquired in classical service-oriented computing. Where being able to distribute and servitize a development has offered benefits already known to all.

To address the current state of quantum services, in this paper, we have decided to use Amazon Braket. Amazon defines Braket as a fully managed quantum computing service. Specifically, Braket provides a development environment to build quantum algorithms, test them on quantum circuit simulators, and run them on different quantum hardware technologies.

Given that Amazon is currently the global leader regarding cloud computing and services technologies through AWS, Braket seems a good alternative to develop quantum services. Nevertheless, since the state of quantum software development is roughly the same in the different existing platforms, we expect similar results to the ones presented in this paper if the quantum services were developed on a different platform.

The basic building block of service-oriented computing is a service, defined as a self-describing, platform-agnostic computational element that supports rapid, low-cost composition of distributed applications (Papazoglou, 2003). However, Braket is not directly prepared to offer the developed quantum algorithms as services that can be invoked through an endpoint to compose a more complex application.

This shortcoming can be addressed by wrapping the quantum algorithm in a classical service. This implies including a classical computer to run the classical service that, in turn, invokes the quantum computer. As far as the authors know, there is currently no way of directly invoking a quantum algorithm as a service. Figure 2 shows an example of this approach. One of the simplest and well-known quantum circuits, the one used to create Bell states between two qubits is wrapped by a Flask[9] service. This Flask service can be deployed in a classical computer and provides a simple way to include quantum algorithms in a complex service-oriented solution.

Next, we present a more complex quantum algorithm used as a case study to identify the problems and limitations of current technology from the perspective of Service-Oriented Computing.

4.1 Integer factorization case study

In order to make the analysis as broad and interdisciplinary as possible, we have decided to select a problem well-known by the scientific community working in quantum computing. At the same time, the selected problem is simple enough to be comprehended by any newcomer. Between the several applications that satisfy both conditions, we have decided to tackle Integer Factorization, more precisely with a particular application of the later denoted Prime Factorization. As we all know, although this fundamental problem in number theory is computationally hard, it is not believed to belong to the NP-hard class of problems (Jiang et al., 2018). Nonetheless, it is a problem that has been used as a basic hardness assumption for cryptographic algorithms, such as the famous RSA algorithm. Thus, integer factorization and identification of new methods to address this task acquire an important role in information security.

There are multiple proposals and algorithms for the solution of this problem, being the most famous Shor's algorithm Nielsen and Chuang (2002). This algorithm is normally described in terms of quantum gates and circuits, suitable for development and execution on machines such as IBM's Q computing chip Haring et al. (2011), but when considering other approaches to quantum computing, such as Adiabatic Quantum Computing based on concepts such as quantum annealing, it is not possible to implement Shor's algorithm directly. Nonetheless, other algorithms have been proposed for prime

[9] https://flask.palletsprojects.com/

```python
from flask import Flask, request, jsonify, send_file
from flask_cors import CORS
import matplotlib.pyplot as plt

from braket.circuits import Circuit
from braket.devices import LocalSimulator

app = Flask(__name__)
CORS(app)

@app.route('/execute', methods=["get"])
def execute_quantum_task():

    bell = Circuit().h(0).cnot(control=0, target=1)
    device = LocalSimulator()
    result = device.run(bell, shots=1000).result()
    counts = result.measurement_counts

    plt.bar(counts.keys(), counts.values())
    plt.xlabel('bitstrings')
    plt.ylabel('counts')
    plt.savefig("result.png")

    return send_file("result.png", mimetype='image/png')

if __name__ == '__main__':
    app.run(host="localhost", port=33888)
```

Braket libraries for quantum computing

Classical wrapping service

Quantum algorithm

Fig. 2 Quantum algorithm wrapped by a classical service

factors, such as the case of the algorithm proposed by Wang et al. in (2020). Thus, in the studies conducted on this paper, these will be the algorithms proposed for integer factorization: Shor's algorithms for quantum machines programmed with quantum circuits and gates, such as Rigetti's Motta et al. (2020) and IonQ's Kielpinski et al. (2002); and integer factorization based on quantum annealing for adiabatic quantum machines such as D-Wave's Hu et al. (2019).

These algorithms also serve as an illustration of a problem derived from the relative novelty of quantum computing and its different existing implementations. Namely, the nonexistence of algorithms with do-it-yourself characteristics. This is mainly due to the complex nature of the problems addressed by quantum computing and to the proximity of the algorithms with the underlying hardware used. This context is producing problems similar to those of the 60s software crisis Moguel et al. (2020), where each algorithm was designed for each particular computing hardware, many times having to recreate the algorithms for each new machine or even for each new increment of the problem. A reminiscent of this is found, for example, when having to generate a new circuit in Shor's algorithm for primes to be factorized. Although this could be done through the use of algorithms to generate these circuits automatically, for the great majority of possible users of quantum computing, the ability to be able to create these types of "meta-algorithms" is beyond their capabilities, complicating the expansion of quantum computing usage out of the specialized field. Thus, it is necessary to offer solutions to non-specialized users for the utilization of quantum computing, such as the case of deployment of quantum services which allow hiding the complexity to users, only providing with entry end-points and returning the results of the execution.

4.2 Integer factorization in Amazon Braket

To illustrate the actual situation of quantum services that can be developed on Amazon Braket, we have translated the above-mentioned integer factorization algorithms to this platform.

At the moment of writing this manuscript, Braket supports three different quantum computer simulators and real quantum computers from three different hardware vendors. Specifically, the supported quantum computers include two vendors whose development is based on quantum circuits, Rigetti and IonQ, and one vendor based on quantum annealing, D-Wave. The integer factorization algorithms have been tested in all supported quantum machines and simulators.

Since the supported simulators are also based on quantum circuits, Shor's algorithm has been used in both, simulators and quantum circuits hardware. Figure 3 shows a fragment

```
def period(a, N, selected_device="LocalSimulator"):
    global Ran_Quantum_period_finding
    Ran_Quantum_period_finding = 1
    num_qubits = 5
    C_reg = [0, 0, 0]
    cr = C_reg
    qc = Circuit()
    Shor1 = qc
    Shor1.x(0)
    Shor1.h(4)
    Shor1.h(4)
#   Shor1.measure(4, C_reg[0]) #TODO operation not implemented
#   # Reinitialize to |0>
#   Shor1.reset(4) #TODO operation not implemented

    Shor1.h(4)
    for k in range(2):
        cmod(Shor1, a)
    if C_reg[0] == 1:
        Shor1.rz(4, pi/2.0)
    Shor1.h(4)

    Shor1.h(4)
    cmod(Shor1, a)
    if C_reg[1] == 1 :
        Shor1.rz(4, pi/2.0)
    if C_reg[0] == 1 :
        Shor1.rz(4, pi/2.0)
    Shor1.h(4)

    result = run_on_device(Shor1, selected_device)

    counts = result.measurement_counts
```

Fig. 3 Fragment of the quantum circuit needed to run Shor's algorithm in Amazon Braket of the quantum period-finding subroutine of Shor's algorithm implemented using Amazon Braket. The complete circuit for Shor's algorithm can be executed without changes in the three simulators and the two circuit-based computers supported by Braket. Nevertheless, is interesting to note that the measurement and reinitialization of qubits supported by many other existing simulators, and that can be therefore found in public implementations of Shor's algorithm, are not supported by Braket. In the figure, this part of the algorithm is left commented as an example. Shor's algorithm can be adapted to avoid the use of these operations which means additional efforts to adapt one of the most well-known algorithms to the specifics of a given quantum platform.

This difference with other existing solutions causes that the implementation presented here only works on certain occasions. For our study, the result obtained or that the integer factorization algorithm does not work in all executions is not of great relevance because our interest is the study and analysis of the behavior of the quantum algorithm from the point of view of service-oriented computing.

Although the quantum circuit would be the same regardless of the quantum hardware or simulator used, the way in which the algorithm is invoked changes depending on where it will be run. Figure 4 shows the Braket invocation code for the three simulators and the two quantum computers supported. As can be seen in the figure, using the local simulator is the most straightforward invocation. To run the algorithms in the other simulators an s3 (Amazon simple storage system) destination has to be defined, where results will be stored, alongside a timeout for polling these results (if the polling timeout is too short, results may not be returned within the polling time). Finally, for running the algorithm on real quantum computers, a recovery task has to be defined. The quantum algorithm execution is an asynchronous operation and the developer is in charge of consulting the results when ready.

Finally, to execute integer factorization on an adiabatic quantum machine, such as D-Wave, one would have to completely rewrite the algorithm, since they are based on the adiabatic theorem closely related to quantum annealing. Thus, the mapping challenge differs from gate-based machines rendering quantum circuits inappropriate. Figure 5 shows the Braket code to factorize the number 21 using a D-Wave quantum machine.

These examples, although small, are enough to remark the current limitations of quantum software from the point of view of service-oriented computing.

```
if(selected_device=="LocalSimulator"):
    device = LocalSimulator()
    return device.run(circuit, shots=1000).result()
elif (selected_device=="SV1"):
    device = AwsDevice("arn:aws:braket:::device/quantum-simulator/amazon/sv1")
    return device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=24*60*60).result()
elif (selected_device=="TN1"):
    device = AwsDevice("arn:aws:braket:::device/quantum-simulator/amazon/tn1")
    return device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=24*60*60).result()
elif (selected_device=="Rigetti"):
    device = AwsDevice("arn:aws:braket:::device/qpu/rigetti/Aspen-8")
    task = device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=5*24*60*60)
    return recover_task_result(task)
elif (selected_device=="IonQ"):
    device = AwsDevice("arn:aws:braket:::device/qpu/ionq/ionQdevice")
    task = device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=5*24*60*60)
    return recover_task_result(task)
elif (selected_device=="Dwave"):
    device = AwsDevice("arn:aws:braket:::device/quantum-simulator/amazon/sv1")
    task = device.run(circuit, s3_folder, shots=1000, poll_timeout_seconds=5*24*60*60)
    return recover_task_result(task)
```

Fig. 4 Fragment of the Amazon Braket code to invoke the Shor's algorithm in different devices

```
sampler=BraketDWaveSampler(s3_folder, 'arn:aws:braket:::device/qpu/d-wave/DW_2000Q_6')
sampler_embedding=EmbeddingComposite(sampler)
h={'s1':580, 's2':420, 's3':144, 's4':128}
J={('s1', 's2'):152, ('s1', 's3'):-144, ('s1', 's4'):-512,
    ('s2', 's3'):16, ('s2', 's4'):-512, ('s3', 's4'):128}
sampleset=sampler_embedding.sample_ising(h, J, num_reads=100)
```

Fig. 5 Fragment of the Amazon Braket code to run the integer factorization algorithm in a D-Wave device

5 Quantum service implementation and its current limitations

After developing the described service, the algorithm was tested to execute on all the defined machines and simulators, and different metrics were used to evaluate its performance and the limitations of including a quantum service in a hybrid system. The following were evaluated: **number of qubits**, since it is one of the main limitations of current quantum computers, and this directly affects the ability to execute the service; the **number of shots**, due to the problems that arise from the characteristics of real quantum computers, mainly noise in the state of the qubits, the experiments must be performed several times or "shots" to be statistically consistent; the **precision of results**, since there is some discrepancy in the results obtained on different machines; the **response times**, this measure corresponds to the time elapsed between sending the request and receiving the result; and the **economic cost** of invoking each solution.

To proceed with the evaluation, several HTTP requests were made from the Postman API client tool[10], which allows making requests to REST APIs and taking the described metrics.

The analysis carried out during and after the experiments allows us to conclude that there is some roughness, limitations, and problems that arise when a quantum piece of software is expected to be provided as a service. The mentioned limitations are not related to the fact that quantum services cannot be built but to the fact that, by implementing quantum services with current service technologies, the potential benefits of Service-Oriented Computing are lost.

For the case study proposed above in Sect. 4, the prime number factorization service, it is not viable to make use of traditional algorithms, but it is possible to take advantage of the benefits offered by quantum computing.

In traditional service-oriented computing, replacing a service with another, even if it is deployed on different hardware architecture, is mostly trivial (at least mostly trivial if all the infrastructure is in place such as the Fig. 1 shows). However, what happens if there is a need to replace a classical service with a quantum service?

Following a similar approach to that described in the definition of classical services, an attempt will be made to replicate the classical architecture by transferring it to the quantum world in order to maintain the quality attributes provided by service-oriented computing. Each aspect of a hybrid classical-quantum architecture will then be analyzed.

Taking into account the early stage of quantum software engineering, as shown in Fig. 6, most of the boxes are empty. Regarding the **implementation layer** of a quantum service, the service business logic must be implemented, as we did for the classic service. But then,

[10] https://www.postman.com/

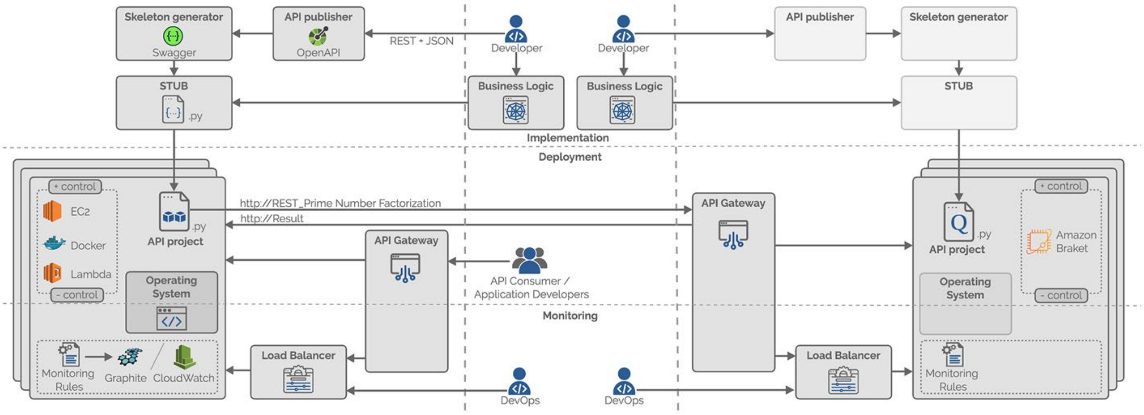


Fig. 6 A hybrid classical-quantum architecture version of a implementation of a service

we have no support or standardization mechanism for the definition of APIs for quantum endpoints. Similarly, there are no tools for code generation at the quantum service level.

In this layer, following a traditional implementation, services must be platform independent. To achieve this, a REST API (based on HTTP, IP and all other well-known Internet protocols) is used to ensure that the services can talk to each other. Similarly, JSON is used as a way to transfer data between services regardless of implementation languages. The use of the OpenAPI specification also helps achieve this independence by providing a way to define a well-formed API that can be easily consumed. However, for a quantum implementation, no communication protocols have been defined, no formatted ways exist for communicating classical services with quantum services, and no specifications even exist for defining an API to achieve service independence. Although there are already researchers who have begun to consider these issues, such as Cuomo et al. (2020) who give an overview of the main challenges and open problems that arise in the design of a distributed quantum computing ecosystem from the perspective of communications engineering; or Rojo et al. (2021) who address the challenge of giving an implementation in the form of a quantum microservice to a well-known problem such as the traveling salesman problem.

Another important feature of service-oriented computing is decoupling. At the implementation layer, the decoupling must be between the services and the programming language in which they are written. In the development of a classic service, this is provided by the OpenAPI specification and code generation tool such as Swagger that are able to generate the Stub of the service in different programming languages. However, in designing a quantum service there are no specifications and code generation tools to generate the stub structure of an API project. Although some work is found such as Dreher and Ramasami (2019) in which they have developed a prototype container-based system that allows a developer to prototype, test and implement quantum algorithms with greater agility and flexibility.

The situation does not improve in the **deployment layer**. At the moment, we have some commercial platforms in which we can execute quantum algorithms. For example, Amazon Braket allow us to run quantum algorithms in different simulators or quantum processors. However, Braket does not offer any control over the platform in which the quantum services will be executed (only one quantum task can be placed in the queue of a quantum processor and wait for a response). Similarly, the API Gateway is not prepared to deal with quantum services.

At this layer, it is also important that services are independent of the location where they are deployed. And from a classic service design perspective, this independence can be considered at two levels. At the physical level, location independence is provided by REST, HTTP, and DNS, which allow us to use a URL to access a service regardless of where it is deployed. At the logical level, location independence for a given service within a more complex project is provided by the API gateway that hides this complexity from clients. But from the point of view of a quantum service, there is no concrete definition, although there are already some works that address these aspects, as in Kumara et al. (2021) that present a vision of Quantum Service-Oriented Computing (QSOC), being a model to build hybrid business applications by placing in collaboration developers of classical services and developers of quantum services; or as Garcia-Alonso et al. (2021) that propose a Quantum API Gateway following the traditional API Gateway pattern and adapting it to the quantum world. Moreover, this Quantum API Gateway recommends the best quantum computer to execute a given quantum service at runtime.

Continuing at the deployment layer, another important feature of service-oriented computing is decoupling. From a classical service design perspective, two different types of decoupling are considered. First, decoupling between different services of the same API. This is provided by the API gateway, which can communicate the services without the services being aware of each other. And second, decoupling between services and hardware and operating systems. This is provided by the platform on which the services are deployed (EC2, Docker, Lambda, etc.). But from the point of view of a quantum service, there is no concrete definition on these decoupling aspects, but there is some work starting to work on this path, as in Grossi et al. (2021) who describe an architectural framework that addresses the problems of integrating an API-exposed quantum provider into an existing enterprise architecture and provides a minimum viable product (MVP) solution that actually merges classical quantum computers into a basic scenario with reusable code in a GitHub repository.

Finally, at the **monitoring layer**, the situation is even worse. In classical service monitoring, there are countless tools, for example *Graphite* or *CloudWatch*; however, there is no support in current tools for monitoring quantum services. The development of this type of tools can offer great benefits to obtain detailed information on the state of quantum services.

In essence, services should be resilient and able to scale to address client demand. The most common way to provide this scalability, without incurring high economic costs on the part of the cloud provider, is the use of elastic platforms and a load balancer that is capable of starting and stopping new instances of the service as needed. But the technology to develop this feature in the quantum world does not yet exist. There are incipient works in this line, such as Sete et al. (2016) in which they describe a functional architecture based on a planar lattice of qubits that allows experimental tests of quantum error correction schemes.

Services should also be composable, so that a set of simple services can be composed to provide a solution to a complex problem. In traditional service development, this composability can be provided by the API Gateway, which can decompose a single invocation into a call to different services without the services knowing about it. However, there is no formal definition for the composability of quantum services. Although there are already different works in this line, such as Wild et al. (2020) in which they introduce two deployment modeling styles based on the Topology and Orchestration Specification for Cloud Applications (TOSCA) standard to automate the deployment and orchestration of quantum applications; or such as Barzen et al. (2020) in which they present a collaborative platform for problem solving with quantum computers; or as Cohen et al. (2020) in which they define a platform for designing quantum control protocols for a wide range of quantum hardware and define how to optimize their performance.

In addition, services must also be reliable, including security, maintainability, accountability, and many other capabilities. In classical services, there is a complete set of monitoring and analysis tools that provide us with all the necessary information about the services. However, in quantum services, there is no progress in this aspect. There is a nascent work, in which researcher You (2020) proposes a framework based on quantum computation for reliability assessment of complex systems.

6 Conclusion and future work

In this paper, and based on what we already know about classical service-oriented computing, we have presented an analysis of current quantum software from the point of view of service-oriented computing. We have used Amazon Braket to deploy quantum services by wrapping them on a classical service and used the integer factorization problem to show the differences of running the same service on different quantum hardware, even when doing it under the common umbrella of Braket.

We have presented a possible implementation of a classical service following the best practices, design patterns, and existing standards. Taking this implementation as a reference, we have developed a replica using a quantum services. This has allowed us to clearly present the current limitations, the proposals that are emerging and the possibilities that we have for the development of quantum services. Given the existing limitations, we have argued that intensive research efforts are needed to bring the benefits of service-oriented computing to the quantum world.

Due to the young nature of quantum software engineering, most areas in this discipline, including service-oriented computing, are still giving their first steps. Nevertheless, the paradigm change that underlies quantum computing implies that there cannot be a direct translation of proposals and techniques. Running quantum algorithms as traditional services is not enough to bring the benefit of service-oriented computing to the quantum era. There needs to be an effort to generate new techniques, methodologies, and tools that bring all these benefits, already shown by cloud and service computing, to quantum software and services.

Acknowledgements This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

Barzen, J., Leymann, F., Falkenthal, M., Vietz, D., Weder, B., & Wild, K. (2020). Relevance of near-term quantum computing in the cloud: A humanities perspective. In: D. Ferguson, C. Pahl, M. Helfert (Eds.), *Cloud Computing and Services Science - 10th International Conference, CLOSER 2020* (vol. 1399, pp. 25–58). Prague, Czech Republic. Revised Selected Papers. Communications in Computer and Information Science. Springer. https://doi.org/10.1007/978-3-030-72369-9_2

Barzen, J., Leymann, F., Falkenthal, M., Vietz, D., Weder, B., & Wild, K. (2020). Relevance of near-term quantum computing in the cloud: a humanities perspective. *Communications in Computer and Information Science*, *1399 CCIS*, 25–58. https://doi.org/10.1007/978-3-030-72369-9_2

Bergholm, V., Izaac, J., Schuld, M., Gogolin, C., Alam, M. S., Ahmed, S., Arrazola, J. M., Blank, C., Delgado, A., & Jahangiri, S., et al. (2018). Pennylane: Automatic differentiation of hybrid quantum-classical computations. arXiv preprint: arXiv:1811.04968.

Boixo, S., Albash, T., Spedalieri, F. M., Chancellor, N., & Lidar, D. A. (2013). Experimental signature of programmable quantum annealing. *Nature Communications, 4*(1), 1–8.

Bouguettaya, A., Singh, M., Huhns, M., Sheng, Q. Z., Dong, H., Yu, Q., et al. (2017). A service computing manifesto: the next 10 years. *Communications of the ACM, 60*(4), 64–72.

Cheng, J. K., Lim, E. M., Krikorian, Y. Y., Sklar, D. J., & Kong, V. J. (2021). A survey of encryption standard and potential impact due to quantum computing. *IEEE Aerospace Conference Proceedings*. https://doi.org/10.1109/AERO50100.2021.9438392

Cohen, Y., Sivan, I., Ofek, N., Ella, L., Drucker, N., Shani, T., Weber, O., Grinberg, H., & Greenbaum, M. (2020). Quantum orchestration platform integrated hardware and software for design and execution of complex quantum control protocols. *Bulletin of the American Physical Society*, *65*(1).

Cuomo, D., Caleffi, M., & Cacciapuoti, A. S. (2020). Towards a distributed quantum computing ecosystem. *IET Quantum Communication, 1*(1), 3–8. https://doi.org/10.1049/IET-QTC.2020.0002

Digital Journal. (2022). Topological quantum computing market is likely to experience a tremendous growth in near future. https://www.digitaljournal.com/pr/topological-quantum-computing-market-is-likely-to-experience-a-tremendous-growth-in-near-future-microsoft-ibm-google-d-wave-systems

Dreher, P., & Ramasami, M. (2019). Prototype container-based platform for extreme quantum computing algorithm development. *2019 IEEE High Performance Extreme Computing Conference*. HPEC 2019. https://doi.org/10.1109/HPEC.2019.8916430

Endrei, M., Ang, J., Arsanjani, A., Chua, S., Comte, P., Krogdahl, P., Luo, M., & Newling, T. (2004). *Patterns: Service-oriented architecture and web services*. IBM Corporation, International Technical Support Organization New York, NY.

Garcia-Alonso, J., Rojo, J., Valencia, D., Moguel, E., Berrocal, J., & Murillo, J. M. (2021). Quantum software as a service through a quantum API gateway. *IEEE Internet Computing*.

Grossi, M., Crippa, L., Aita, A., Bartoli, G., Sammarco, V., Picca, E., Said, N., Tramonto, F., & Mattei, F. (2021). *A serverless cloud integration for quantum computing*. arXiv:2107.02007.

Haring, R., Ohmacht, M., Fox, T., Gschwind, M., Satterfield, D., Sugavanam, K., et al. (2011). The IBM blue gene/q compute chip. *IEEE Micro, 32*(2), 48–60.

Haugeland, S. G., Nguyen, P. H., Song, H., & Chauvel, F. (2021). Migrating monoliths to microservices-based customizable multi-tenant cloud-native apps. *Proceedings - 2021 47th Euromicro Conference on Software Engineering and Advanced Applications, SEAA 2021* (pp. 170–177). https://doi.org/10.1109/SEAA53835.2021.00030

Hu, F., Wang, B. -N., Wang, N., & Wang, C. (2019). Quantum machine learning with d-wave quantum computer. *Quantum Engineering, 1*(2), 12.

Hooton, C. (2019). Examining the economic contributions of the cloud to the united states economy. Report. Internet Association. Washington, DC.

Jiang, S., Britt, K. A., McCaskey, A. J., Humble, T. S., & Kais, S. (2018). Quantum annealing for prime factorization. *Scientific Reports, 8*(1), 1–9.

Kielpinski, D., Monroe, C., & Wineland, D. J. (2002). Architecture for a large-scale ion-trap quantum computer. *Nature, 417*(6890), 709–711.

Kumara, I., Heuvel, W. -J. V. D., & Tamburri, D. A. (2021). QSOC: Quantum service-oriented computing. In: *Symposium and Summer School on Service-Oriented Computing* (pp. 52–63). Springer. https://doi.org/10.1007/978-3-030-87568-8_3, https://link.springer.com/chapter/10.1007/978-3-030-87568-8_3

MacQuarrie, E. R., Simon, C., Simmons, S., & Maine, E. (2020). The emerging commercial landscape of quantum computing. *Nature Reviews Physics, 2*(11), 596–598.

Mazlami, G., Cito, J., & Leitner, P. (2017). Extraction of microservices from monolithic software architectures. *Proceedings - 2017 IEEE 24th International Conference on Web Services, ICWS 2017* (pp. 524–531). https://doi.org/10.1109/ICWS.2017.61

McCaskey, A. J., Lyakh, D. I., Dumitrescu, E. F., Powers, S. S., & Humble, T. S. (2020). Xacc: a system-level software infrastructure for heterogeneous quantum-classical computing. *Quantum Science and Technology, 5*(2), 024002.

McCaskey, A., Dumitrescu, E., Liakh, D., & Humble, T. (2018). Hybrid programming for near-term quantum computing systems. In: *2018 IEEE International Conference on Rebooting Computing (ICRC)* (pp. 1–12). IEEE.

Moguel, E., Berrocal, J., García-Alonso, J., & Murillo, J. M. (2020). A roadmap for quantum software engineering: Applying the lessons learned from the classics. In: R. Pérez-Castillo, M. Piattini, G. Peterssen, J. L.Hevia (Eds.), *Short Papers Proceedings of the 1st International Workshop on Software Engineering & Technology (Q-SET'20) Co-located with IEEE International Conference on Quantum Computing and Engineering (IEEE Quantum Week 2020), (Online Conference)* (vol. 2705, pp. 5–13). Broomfield, Colorado, USA. CEUR Workshop Proceedings. CEUR-WS.org. http://ceur-ws.org/Vol-2705/short1.pdf

Motta, M., Sun, C., Tan, A. T., O'Rourke, M. J., Ye, E., Minnich, A. J., et al. (2020). Determining eigenstates and thermal states on a quantum computer using quantum imaginary time evolution. *Nature Physics, 16*(2), 205–210.

Newman, S. (2021). Building microservices. Oreilly.

Nielsen, M. A., & Chuang, I. (2002). Quantum computation and quantum information. American Association of Physics Teachers.

Papazoglou, M. P. (2003). Service-oriented computing: Concepts, characteristics and directions. In: *Proceedings of the Fourth International Conference on Web Information Systems Engineering*, 2003 (pp. 3–12). WISE 2003. IEEE.

Pérez-Castillo, R., Serrano, M. A., & Piattini, M. (2021). Software modernization to embrace quantum technology. *Advances in Engineering Software, 151,* 102933.

Pérez-Castillo, R., & Piattini, M. (2020). The quantum software engineering path. In: R. Pérez-Castillo, M. Piattini, G. Peterssen, J. L. Hevia (Eds.), *Short Papers Proceedings of the 1st International Workshop on Software Engineering & Technology (Q-SET'20) Co-located with IEEE International Conference on Quantum Computing and Engineering (IEEE Quantum Week 2020)* (vol. 2705, pp. 1–4). Broomfield, Colorado, USA. CEUR Workshop Proceedings. CEUR-WS.org. http://ceur-ws.org/Vol-2705/invited1.pdf

Piattini, M., Peterssen, G., & Pérez-Castillo, R. (2020). Quantum computing: a new software engineering golden age. *ACM SIGSOFT Softw Eng Notes, 45*(3), 12–14. https://doi.org/10.1145/3402127.3402131

Piattini, M., Serrano, M., Perez-Castillo, R., Petersen, G., & Hevia, J. L. (2021). Toward a quantum software engineering. *IT Professional, 23*(1), 62–66.

Piattini, M., Peterssen, G., Pérez-Castillo, R., Hevia, J. L., Serrano, M. A., Hernández, G., de Guzmán, I. G. R., Paradela, C. A., Polo, M., Murina, E., Jiménez, L., Marqueño, J. C., Gallego, R., Tura, J., Phillipson, F., Murillo, J. M., Niño, A., & Rodríguez, M. (2020). The talavera manifesto for quantum software engineering and programming. In: *Short Papers Proceedings of the 1st International Workshop on the Quantum Software Engineering & Programming* (vol. 2561, pp. 1–5). Talavera de la Reina, Spain. CEUR Workshop Proceedings.

Pistoia, M., Ahmad, S. F., Ajagekar, A., Buts, A., Chakrabarti, S., Herman, D., Hu, S., Jena, A., Minssen, P., Niroula, P., Rattew, A., Sun, Y., & Yalovetzky, R. (2021). Quantum machine learning for finance. arXiv:2109.04298. https://doi.org/10.1109/ICCAD51958.2021.9643469

Rahaman, M., & Islam, M. M. (2015). A review on progress and problems of quantum computing as a service (GCAAS) in the perspective of cloud computing. *Global Journal of Computer Science and Technology.*

Ravichandran, T., & Rai, A. (2000). Quality management in systems development: an organizational system perspective. *MIS Quarterly: Management Information Systems, 24*(3), 381–410. https://doi.org/10.2307/3250967

Richardson, C. (2019). *Microservices Patterns* (p. 490). Manning Publications.

Rojo, J., Valencia, D., Berrocal, J., Moguel, E., Garcia-Alonso, J., & Rodriguez, J. M. M. (2021). *Trials and tribulations of developing hybrid quantum-classical microservices systems*. arXiv:2105.04421

Sete, E. A., Zeng, W. J., & Rigetti, C. T. (2016). A functional architecture for scalable quantum computing. *2016 IEEE International Conference on Rebooting Computing*. ICRC 2016 - Conference Proceedings. https://doi.org/10.1109/ICRC.2016.7738703

Sodhi, B. (2018). Quality attributes on quantum computing platforms. arXiv preprint: arXiv:1803.07407

Wang, B., Hu, F., Yao, H., & Wang, C. (2020). Prime factorization algorithm based on parameter optimization of Ising model. *Scientific Reports, 10*(1), 1–10.

Wang, L., Von Laszewski, G., Younge, A., He, X., Kunze, M., Tao, J., & Fu, C. (2010). Cloud computing: a perspective study. *New Generation Computing, 28*(2), 137–146.

Wild, K., Breitenbucher, U., Harzenetter, L., Leymann, F., Vietz, D., & Zimmermann, M. (2020). TOSCA4QC: Two modeling styles for TOSCA to automate the deployment and orchestration of quantum applications. *Proceedings - 2020 IEEE 24th International Enterprise Distributed Object Computing Conference* (pp. 125–134). EDOC 2020. https://doi.org/10.1109/EDOC49727.2020.00024

Wille, R., Van Meter, R., & Naveh, Y. (2019). IBM's qiskit tool chain: Working with and developing for real quantum computers. In: *2019 Design, Automation & Test in Europe Conference & Exhibition (DATE)* (pp. 1234–1240). IEEE.

Wolff, E. (2019). *Microservices - a practical guide: Principles, concepts, and recipes*. Lean Publishing.

You, S. (2020). A quantum computing framework for complex system reliability assessment. arXiv:2012.03919.

Zhao, J. (2020). Quantum software engineering: Landscapes and horizons. CoRR abs/2007.07047. arXiv:2007.07047

Zinner, M., Dahlhausen, F., Boehme, P., Ehlers, J., Bieske, L., & Fehring, L. (2022). *Drug Discovery Today, 27*(2), 378–383. https://doi.org/10.1016/J.DRUDIS.2021.10.006

Enrique Moguel is an assistant professor at the University of Extremadura (Spain). He completed his MSc in Computer Science at the University Carlos III (Spain) in 2010 and a PhD in Computer Science at the University of Extremadura in 2018. His research interests include Web Engineering, Smart Systems, and Quantum Computing.

Javier Rojo is a PhD student at the University of Extremadura. He has a predoctoral position at the same university, through a grant for the formation of university professors, from the Spanish Ministry of Science, Innovation and Universities. He completed his MSc. in Computer Science at the University of Extremadura in 2021. His research interests include software engineering, eHealth, pervasive computing, and mobile computing.

David Valencia is a postdoctoral researcher at the University of Extremadura (Spain). He completed his MSc (2004) and PhD (2010) in Computer Science at the University of Extremadura (Spain). His research interests include Quantum Computing, Parallel and Distributed Computing, and Software Engineering.

Javier Berrocal is an associate professor in the Department of Informatics and Telematics System Engineering at the University of Extremadura (Spain) and co-founder of the Startup Gloin. He completed his PhD degree (with European Mention) in 2014. His research interests include mobile computing, context awareness, pervasive systems, the Internet of Things, and fog computing.

Jose Garcia-Alonso is an associate professor in the Department of Informatics and Telematics System Engineering at the University of Extremadura (Spain) and co-founder of the Startups Gloin, Viable and Health and Ageing Tech. He completed his PhD degree (with European Mention) in 2014. His main research interests are in Quantum Software Engineering, eHealthCare, eldercare, Mobile Computing, Context-Awareness, and Pervasive Systems.

Juan M. Murillo is a full professor of software engineering at the University of Extremadura and co-founder of the Startups Gloin and Viable. His research interests include Quantum Software Engineering, software architectures, mobile computing, and cloud computing.

Authors and Affiliations

Enrique Moguel[1] · **Javier Rojo**[1] · **David Valencia**[1] · **Javier Berrocal**[1] · **Jose Garcia-Alonso**[1] · **Juan M. Murillo**[1]

Javier Rojo
javirojo@unex.es

David Valencia
davaleco@unex.es

Javier Berrocal
jberolm@unex.es

Jose Garcia-Alonso
jgaralo@unex.es

Juan M. Murillo
juanmamu@unex.es

1 Quercus Software Engineering Group, Universidad de Extremadura, Avda. de la Universidad, s/n, Cáceres 10004, Spain

Appendix N

Quantum software as a service through a quantum API gateway (Summary)

Authors: *Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, Juan Manuel Murillo.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2022.*

Handle: *11705/JCIS/2022/002*

Quantum Software as a Service Through a Quantum API Gateway (Summary)*

Jose Garcia-Alonso[1 [0000−0002−6819−0299]], Javier Rojo[1 [0000−0001−9189−1133]], David Valencia[1 [0000−0001−5571−2142]], Enrique Moguel[1 [0000−0002−4096−1282]], Javier Berrocal[1 [0000−0002−1007−2134]], and Juan M. Murillo[1 [0000−0003−4961−4030]]

Universidad de Extremadura, Spain {jgaralo, javirojo, davaleco, enrique, jberolm, juanmamu}@unex.es

Summary of the Contribution

As quantum computers mature, the complexity of quantum software increases. As we move from the initial standalone quantum algorithms toward complex solutions combining quantum algorithms with traditional software, new software engineering methods and abstractions are needed. Nowadays, quantum computers are usually offered in the cloud, under a pay-per-use model, leading to the adoption of the service-oriented good practices that dominate the cloud today. However, specific adaptations are needed to reap the benefits of service-oriented computing while dealing with quantum hardware limitations. In this paper, we propose the Quantum API Gateway—an adaptation of the API Gateway pattern that takes into account the fact that quantum services cannot be deployed as traditional services. Instead, the Quantum API Gateway recommends the best quantum computer to run a specific quantum service at run-time. As proof of concept, we provide an implementation of the Quantum API Gateway for the Amazon Braket platform.

Keywords: Quantum Computing · Quantum Services · Service Computing · AWS · API Gateway.

Acknowledgments

This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), the FPU19/03965 grant, the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and the European Regional Development Fund.

* This work has been published in IEEE Internet Computing, vol. 26, 2021. JCR 2020: 2.341, 43/108, Q2. https://doi.org/10.1109/MIC.2021.3132688

Appendix O

SOWCompact: A federated process mining method for social workflows (Summary)

Authors: *Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, Carlos Canal.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2022.*

Handle: *11705/JCIS/2022/001*

SOWCompact: A federated process mining method for social workflows (Summary)*

Javier Rojo[1][0000−0001−9189−1133], José García-Alonso[1][0000−0002−6819−0299], Javier Berrocal[1][0000−0002−1007−2134], Juan Hernández[1][0000−0002−6343−7395], Juan M. Murillo[1][0000−0003−4961−4030], and Carlos Canal[2][0000−0002−8002−0372]

[1] Universidad de Extremadura
{javirojo,jgaralo,jberolm,juanher,juanmamu}@unex.es
[2] Universidad de Málaga
canal@lcc.uma.es

Summary of the Contribution

The growing informatization of the environment allows modeling people's behavior as a social workflow, where both individual actions and interactions with other people are captured. This modelling includes actions that are part of an individual's routine, as well as less frequent events. Although infrequent actions may provide relevant information, it is routine behaviors that characterize users. However, the extraction of this knowledge is not simple. There are problems when analyzing together large amounts of traces from many users, resulting into a social workflow that does not clearly depict their behavior, either individually or as a group. Tools that allow grouping/filtering of users with a common behavior pattern are needed, to analyze each of these groups separately. This study presents the federated process mining and an associated tool, SOWCompact. Its potential is validated through the case study called activities of daily living (ADL). Using federated process mining, along with current process mining techniques, more compact processes using only the social workflow's most relevant information are obtained, while allowing the analysis of these social workflows.

Keywords: process mining · pattern discovery · social workflows · federated process mining

Acknowledgments

This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020), RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), and UMA18-FEDERJA-180 (Junta de Andalucía/ATech/FEDER), by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), by the FPU19/03965 grant and by the European Regional Development Fund.

* This work has been published in Information Sciences, vol. 595, 2022. JCR 2020: 6.795, 18/161, Q1. https://doi.org/10.1016/j.ins.2022.02.035

Appendix P

Arquitectura Orientada a Servicios basada en Computación Cuántica para farmacogenética

Authors: *Jaime Alvarado-Valiente, Javier Romero-Alvarez, Javier Rojo, Enrique Moguel, Jose García-Alosno, Juan M. Murillo.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2022.*

Handle: *11705/JCIS/2022/025*

Arquitectura Orientada a Servicios basada en Computación Cuántica para farmacogenética

Jaime Alvarado-Valiente[1][0000−0003−0140−7788], Javier Romero-Álvarez[1][0000−0002−3162−1446], Javier Rojo[1][0000−0001−9189−1133], Enrique Moguel[2][0000−0002−4096−1282], José García-Alonso[1][0000−0002−6819−0299], and Juan M. Murillo[1][0000−0003−4961−4030]

[1] Universidad de Extremadura, Escuela Politécnica, Quercus Software Engineering Group,
Av. de la Universidad, S/N, 10003, Cáceres, Spain
{jaimeav, jromero, javirojo, jgaralo, juanmamu}@unex.es
[2] Universidad de Extremadura, Centro Universitario de Mérida, Quercus Software Engineering Group
enrique@unex.es

Abstract. La farmacogenética es una disciplina que tiene y tendrá mucha relevancia en el campo de la medicina y la medicación personalizada. Esta disciplina permite el estudio de los efectos de la variabilidad genética de un individuo en su respuesta a determinados fármacos. Sin embargo, generar una terapia farmacológica segura y eficaz ayudándose de las herramientas computacionales que tenemos en la actualidad es un problema complejo. La computación cuántica promete resolver este tipo de problemas que son inabarcables en tiempo y forma para la computación clásica. Por todo ello, proponemos un sistema software híbrido clásico-cuántico, que permite la simulación de posibles efectos de un tratamiento farmacológico en una persona mayor con ciertos factores genéticos.

Keywords: Computación Cuántica · Sistemas híbridos · Sistemas clásico-cuánticos · Farmacogenética · Envejecimiento.

1 Introducción

El 19,5% de la población europea tiene más de 65 años, y se prevé que este dato aumente debido al descenso de la natalidad y al aumento en la esperanza de vida [1]. El envejecimiento en sí mismo no es un problema, al menos no directamente. Sin embargo, problemas como el deterioro cognitivo, los trastornos nutricionales o los problemas de salud gravan los efectos negativos del envejecimiento.

En la mayoría de ocasiones, los profesionales de la salud tratan estos problemas a través de la medicación, ya que la mayoría son procesos crónicos con bastantes afecciones coadyuvantes que limitan la calidad de vida del anciano. Generalmente, los ancianos con alguna patología se encuentra polimedicados [2]. Lo que quiere decir que están en tratamiento farmacológico de más de 3 fármacos. El tratamiento farmacológico en las personas mayores es necesario para tratar la mayoría de las enfermedades, para mejorar su salud o prevenir un mayor deterioro. Por consiguiente, los expertos sanitarios tienen que tener especial cuidado, debido a que una prescripción inadecuada o incompatibilidad entre fármacos puede derivar en problemas importantes para el paciente [3].

En este contexto, la farmacogenética permite el estudio de los efectos de la variabilidad genética de un individuo en su respuesta a determinados fármacos. En otras palabras, esta disciplina permite realizar la prescripción de medicamentos teniendo en cuenta los posibles efectos que éstos puedan tener en un paciente con unos factores genéticos concretos. Sin embargo, proporcionar una terapia farmacológica segura y eficaz haciendo uso de los sistemas software tradicionales es una tarea compleja, desde el punto de vista computacional y de altas necesidades de tiempo de procesamiento [4].

Este tipo de problemas, que no pueden ser resueltos en tiempo y forma con la computación clásica, pueden ser resueltos haciendo uso de la computación cuántica. Ésta, no sólo permite resolver problemas en mucho menos tiempo que los ordenadores clásicos, sino que también permite utilizar su potencia de cálculo para abordar problemas que van más allá del alcance de la computación clásica tal y como la conocemos [5, 6]. En particular, la potencia de los ordenadores cuánticos se debe a su capacidad para resolver problemas del tipo BQP (por las siglas en inglés de *Bounded-error Quantum Polynomial time problems*). Este es el conjunto de problemas que puede ser resuelto por una computadora cuántica en un tiempo polinomial dentro de un determinado margen de error, y el problema que se aborda en el presente artículo así lo es.

En este artículo se propone un sistema híbrido clásico-cuántico que, haciendo uso de las ventajas de la computación cuántica, permita servir de soporte tecnológico a los expertos sanitarios para la preparación de conjuntos de datos y la extracción de las relaciones entre las distintas variables farmacogenómicas. De esta manera, la herramienta permitirá a los sanitarios realizar consultas complejas y facilitar la visualización de la información. Con ello, se podrá predecir los posibles efectos adversos que un determinado fármaco pueda tener sobre la salud de una persona en función de su historial farmacológico y condición genética. Los resultados vertidos por el sistema permitirá ayudar en la toma de decisiones a los expertos sanitarios para la implantación de un tratamiento farmacológico a un paciente determinado con unas condiciones genómicas particulares.

2 Sistema sanitario para la administración farmacológica basado en la simulación cuántica

La computación orientada a servicios y las arquitecturas SOA han sido el centro de una intensa investigación que ha llevado a que el software monolítico sea reemplazado por el software basado en servicios [7]. Siguiendo con los conocimientos adquiridos en estos ámbitos, podemos hacer uso de las prácticas, patrones de diseño y estándares de los servicios clásicos en el mundo cuántico [8].

Tal y como se muestra en la Figura 1, la solución propuesta de sistema sanitario cuántico se divide en dos capas (*Back-end* y *Front-end*):

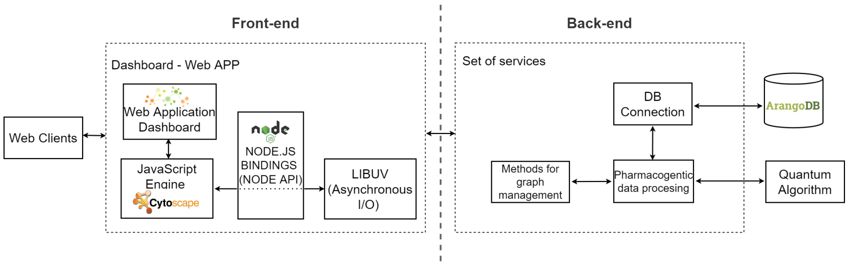


Fig. 1. Diagrama de la arquitectura del sistema sanitario

El ***Back-end*** consta principalmente de un conjunto de componentes y servicios encargados de realizar las operaciones y conexiones con la base de datos de ArangoDB[3], donde se encuentra almacenada la información de interés de las variables farmacogenéticas y sus relaciones. Estos servicios son los responsables de todo el tratamiento de los datos y de ofrecer la lógica de negocio que se expone mediante la aplicación web. El uso del algoritmo cuántico permite ejecutar el proceso de simulación cuántica, utilizando las relaciones entre los datos para alimentar el algoritmo. El estudio y diseño de este algoritmo se basa en técnicas de Machine Learning para predecir cómo actuaría un determinado fármaco dadas unas características concretas del paciente. Su conexión con el sistema se lleva a cabo con métodos híbridos clásico-cuánticos, como son los ofrecidos por Amazon Braket[4] e IBM[5].

Con respecto al ***Front-end*** del sistema, éste permite la visualización y manipulación de los datos de los pacientes mediante una aplicación web que actúa como cuadro de mandos para los sanitarios. Esta aplicación está desarrollada con el framework Node.js para hacer que la adaptación de las diferentes librerías de Javascript sea más fácil, como la de la biblioteca CytoscapeJS[6], la cual permite la visualización y manipulación de los grafos. Estos grafos posibilitan a los sanitarios visualizar el historial médico de los pacientes, además de las relaciones que existen entre los nodos (fármacos, factores clínicos, efectos adveros, etc.). Además, este artefacto del sistema se encarga de ofrecer diferentes funcionalidades para que el usuario pueda realizar las operaciones que se permitan hacer con la herramienta como, por ejemplo, la carga de datos o invocar las diferentes operaciones que ofrecen los servicios del *Back-end*.

3 Conclusiones

Las personas mayores con enfermedades crónicas suelen estar polimedicadas. Por ello, los expertos sanitarios tienen que tener especial cuidado a la hora de re-

[3] https://www.arangodb.com/
[4] https://aws.amazon.com/es/braket/
[5] https://quantum-computing.ibm.com/
[6] https://js.cytoscape.org/

alizar la prescripción de medicamentos. Sin embargo, proporcionar una terapia farmacológica segura y eficaz con el software clásico actual es un problema complejo y con la actual tecnología no es posible resolverlo en tiempo y forma. En este trabajo se presenta una solución sanitaria que utiliza la computación cuántica para optimizar la administración de medicamentos. Concretamente, se trata de un sistema híbrido clásico-cuántico que es capaz de realizar optimizaciones y simulaciones para predecir los posibles efectos adversos de un determinado medicamento en las personas que envejecen.

Este es un trabajo incipiente que creemos que puede suponer una revolución tecnológica en el sector sanitario. Todavía queda mucho trabajo por hacer y retos que resolver, porque el campo del software cuántico es reciente, con nuevas tecnologías cuánticas que surgen día a día y con la necesidad de aplicar las diferentes técnicas de la ingeniería del software cuántico.

4 Agradecimientos

Este trabajo ha sido parcialmente financiado por el proyecto 0499_4IE_PLUS _4_E (Interreg V-A España-Portugal 2014-2020); por el Ministerio de Ciencia, Innovación y Universidades (el proyecto RTI2018-094591-B-I00 y la ayuda FPU19 / 03965); el proyecto QSalud; la Consejería de Economía e Infraestrutura de la Junta de Extremadura (GR18112, IB18030) cofinanciado por el Fondo Europeo de Desarrollo Regional (FEDER).

Referencias

1. H. T. Khan, "Population ageing in a globalized world: Risks and dilemmas?" *Journal of evaluation in clinical practice*, vol. 25, no. 5, pp. 754–760, 2019.
2. N. Khan, R. Kaestner, and S.-J. Lin, "Effect of prescription drug coverage on health of the elderly," *Health services research*, vol. 43, no. 5p1, pp. 1576–1597, 2008.
3. M. N. O'Connor, P. Gallagher, and D. O'Mahony, "Inappropriate prescribing," *Drugs & aging*, vol. 29, no. 6, pp. 437–452, 2012.
4. M. Senbekov, T. Saliev, Z. Bukeyeva, A. Almabayeva, M. Zhanaliyeva, N. Aitenova, Y. Toishibekov, and I. Fakhradiyev, "The recent progress and applications of digital technologies in healthcare: a review," *International journal of telemedicine and applications*, vol. 2020, 2020.
5. E. Moguel, J. Berrocal, J. García-Alonso, and J. M. Murillo, "A roadmap for quantum software engineering: Applying the lessons learned from the classics." in *Q-SET@ QCE*, 2020, pp. 5–13.
6. M. Piattini, G. Peterssen, and R. Pérez-Castillo, "Quantum computing: A new software engineering golden age," *ACM SIGSOFT*, vol. 45, no. 3, pp. 12–14, 2021.
7. M. N. Huhns and M. P. Singh, "Service-oriented computing: Key concepts and principles," *IEEE Internet computing*, vol. 9, no. 1, pp. 75–81, 2005.
8. E. Moguel, J. Rojo, D. Valencia, J. Berrocal, J. Garcia-Alonso, and J. M. Murillo, "Quantum service-oriented computing: current landscape and challenges," *Software Quality Journal 2022*, pp. 1–20, 4 2022. [Online]. Available: https://link.springer.com/article/10.1007/s11219-022-09589-y

Appendix Q

Generación de Servicios Cuánticos ampliando la especificación OpenAPI

Authors: *Javier Romero-Alvarez, Jaime Alvarado-Valiente, Javier Rojo, Enrique Moguel, Jose García-Alosno, Juan M. Murillo.*

Publication type: *Conference paper (National).*

Conference: *Jornadas de la Ciencia e Ingeniería de Servicios (JCIS).*

Year of publication: *2022.*

Handle: *11705/JCIS/2022/021*

Generación de Servicios Cuánticos ampliando la especificación OpenAPI

Javier Romero-Álvarez[1[0000−0002−3162−1446]], Jaime Alvarado-Valiente[1[0000−0003−0140−7788]], Javier Rojo[1[0000−0001−9189−1133]], Enrique Moguel[2[0000−0002−4096−1282]], José García-Alonso[1[0000−0002−6819−0299]], and Juan M. Murillo[1[0000−0003−4961−4030]]

[1] Universidad de Extremadura, Escuela Politécnica, Quercus Software Engineering Group,
Av. de la Universidad, S/N, 10003, Cáceres, Spain
`{jromero, jaimeav, javirojo, jgaralo, juanmamu}@unex.es`

[2] Universidad de Extremadura, Centro Universitario de Mérida, Quercus Software Engineering Group
`enrique@unex.es`

Abstract. Tras décadas de avances, fundamentalmente teóricos, en los últimos años la computación cuántica ha comenzado a ver sus primeras aplicaciones prácticas. Esta nueva y revolucionaria tecnología pretende potenciar áreas tan importantes como la Inteligencia Artificial, la Ciberseguridad o la Medicina. El auge de esta tecnología ha auspiciado que diferentes centros de investigación y grandes empresas como Google, Microsoft, IBM o Amazon estén dedicando notables esfuerzos en desarrollar nuevas tecnologías que lleven la computación cuántica al mercado. Sin embargo, estas tecnologías no están todavía lo suficientemente maduras y existe una alta dependencia de las plataformas. Es por ello, que debemos idear y desarrollar nuevas herramientas que faciliten el acceso a esta tecnología y permitan aumentar el nivel de abstracción con el que se trabaja. Dado que la integración del software cuántico no debería ser muy diferente a la de los servicios clásicos, podemos aprovechar los conocimientos adquiridos y emplear las técnicas actuales de la Ingeniería de Servicios. Por ello, proponemos la definición de un modelo para la servitización de algoritmos cuánticos mediante la ampliación de la especificación OpenAPI. Esta nueva extensión de la especificación permite la definición y generación de código para servicios cuánticos, favoreciendo la integración y desarrollo de servicios híbridos clásico-cuánticos.

Keywords: Ingeniería de Servicios · Programación cuántica · Software Cuántico · Servicios híbridos clásico-cuánticos · OpenAPI

1 Introducción

La computación cuántica ha pasado de la ciencia ficción a la realidad. Los ordenadores basados en los principios de la teoría cuántica, que introdujo el físico Max Plank [1], están cada vez más presentes. Debido a lo cual, este nuevo paradigma está generando grandes expectativas y promete revolucionar la ciencia tal y como la conocemos [2]. Aunque ésta no es una tecnología que estará presente en los hogares de las personas, como sí lo es la computación clásica, sí que será útil para realizar ciertas tareas que la computación tradicional no puede hacer en tiempo y forma razonables. La ciberseguridad, la biomedicina o la economía son algunos de los ámbitos que vivirán una gran revolución gracias a los avances en computación cuántica [3–5]. En definitiva, muchos de los problemas que hasta ahora no se podían resolver, los denominados de tiempo polinomial cuántico de error acotado (BQP) [6], podrán ser resueltos por ordenadores cuánticos, aunque tendrán que coexistir y apoyarse en la computación clásica.

Una señal del auge de esta tecnología es que las mayores empresas tecnológicas del mundo, entre las que se encuentran Google, Microsoft, IBM o Amazon, están haciendo una gran inversión en el desarrollo de este tipo de tecnología, persiguiendo la llamada supremacía cuántica [7]. Actualmente, la forma en la que estas empresas ofrecen las máquinas cuánticas es mediante Plataforma como Servicio (*Platform as a Service*, PaaS), al igual que la mayoría de los sistemas clásicos. Esto nos hace pensar que la manera lógica de consumir este tipo de tecnología sea mediante servicios.

Desde el punto de vista de la computación orientada a servicios, la integración del software cuántico no debería ser muy diferente de los servicios clásicos [8]. Sin embargo, hoy en día, la falta de técnicas de Ingeniería de Software para servicios cuánticos se ve afectada por muchos niveles como, por ejemplo, el poco nivel de abstracción con el que se trabaja. Para resolver este problema, empiezan a surgir alternativas que trasladan los procesos clásicos a la computación cuántica. Estas aproximaciones se centran en la Ingeniería del Software Clásico [9].

De esta manera, uno de los modelos que se está empezando a utilizar es el de la Computación Cuántica como Servicio (*Quantum Computing as a Service*, QCaaS) [10], un modelo que facilita el acceso a la tecnología cuántica a través de la nube. No obstante, todavía no es agnóstico del hardware, por lo que se deben desarrollar nuevas herramientas para facilitar su desarrollo. Hay autores que ya han abordado algunas metodologías para intentar aumentar el nivel de abstracción [11] o tratar algunas actividades como el diseño [12].

Para abordar este problema y aprovechar las ventajas que nos ofrece la Ingeniería de Servicios en la computación cuántica, proponemos generar servicios cuánticos dada una especificación y el código del circuito cuántico, haciendo uso de la especificación OpenAPI [13]. Esta herramienta permite definir y generar el código de los servicios que pueden ser invocados como servicios web RESTful.

El código de las aplicaciones cuánticas a generar será en lenguaje Python, por su facilidad de integración con las diferentes herramientas utilizadas en el desarrollo de este trabajo, como es el compositor cuántico ofrecido por IBM[3]. Con este compositor se generará el código cuántico de los algoritmos a servitizar. Concretamente, como prueba y validación de concepto, presentamos la servitización de un algoritmo de generación de números aleatorios [14], algoritmo que aprovecha la naturaleza de la mecánica cuántica para generar un número realmente aleato-

[3] https://quantum-computing.ibm.com/composer

rio. Para ello, proponemos la especificación de una Interfaz de Programación de Aplicaciones (*Application Programming Interface*, API) utilizando el formato OpenAPI y de una versión extendida de la herramienta OpenAPI Generator[4], una herramienta diseñada para crear bibliotecas de clientes de API, configuraciones y documentación a partir de documentos OpenAPI.

Este artículo se estructura de la siguiente forma: la Sección 2 motiva el trabajo presentado. La Sección 3 presenta la propuesta de generación de servicios de APIs cuánticas mediante una extensión de la especificación OpenAPI, concretamente para el algoritmo de generación de números aleatorios. Y por último, la Sección 4 detalla las conclusiones del trabajo.

2 Motivación

Estamos empezando a encontrar nuevas investigaciones relacionadas con este nuevo paradigma de la computación tanto a nivel de hardware, como a nivel de software [4]. Durante la evolución de la Ingeniería de Software Clásico se ha podido comprobar que el software necesita procesos y estos, a su vez, necesitan de metodologías que ayuden a llevar a cabo cada una de las actividades de los procesos, ya sea la especificación, el diseño arquitectónico, la implementación o las pruebas. En lo que respecta al proceso de desarrollo de software cuántico, cabe suponer que las estrategias básicas del desarrollo de software clásico podrían ser válidas [8]. De aquí surge el interés que está despertando la Ingeniería del Software Cuántico [15], la cual tiene que definir metodologías similares a la clásica para cada una de las actividades del proceso de desarrollo de software cuántico. Para abordar esta cuestión, las diferentes técnicas y metodologías de la ingeniería clásica deberían aplicarse al ámbito de la computación cuántica [16].

Esto nos hace ver que el modo en el que ambas tecnologías coexistirán será mediante arquitecturas híbridas clásico-cuánticas en las que trabajarán en conjunto para resolver problemas y ofrecer las soluciones a los usuarios [15].

Actualmente, los ordenadores cuánticos se ofrecen como PaaS mediante proveedores cloud como AWS, IBM, Google Cloud o Azure, y dado los costes que supone la construcción y mantenimiento de estos, podemos pensar que esto seguirá siendo así [17]. Por ello, se deben desarrollar propuestas que consigan integrar la computación cuántica con la clásica. Para lograr esta integración se está trabajando en aplicar todo el conocimiento adquirido sobre la computación clásica en la computación cuántica. Una propuesta para esta integración es la servitización del software cuántico mediante arquitecturas orientadas a servicios [18, 19]. Esto pondría a disposición de la computación clásica el software cuántico con protocolos de invocación y comunicación ya existentes, donde se ofrecerían servicios que encapsulan el software cuántico. De esta forma, estos servicios cuánticos podrían ser invocados mediante métodos REST y devolver el resultado obtenido para que el software clásico lo procese. La forma de crear estos servicios cuánticos que existe actualmente es muy manual, debido a que no existen herramientas que agilicen el desarrollo de este tipo de software.

[4] https://openapi-generator.tech/

Como consecuencia, surge la necesidad de diseñar nuevas herramientas que permitan agilizar su desarrollo, al igual que existen para el software clásico [13], de manera que sean capaces de tratar las características de la computación cuántica. En este contexto, para llevar a cabo la definición y especificación de un servicio clásico y pudiendo aplicarse a la definición de servicios cuánticos, los desarrolladores software necesitan combinar dos aspectos principales: la lógica de negocio del servicio, que es específica de cada servicio, y el *endpoint* del servicio. Para el diseño y la documentación de estos *endpoints* y APIs complejas, se puede utilizar la especificación OpenAPI y su generador de código. OpenAPI es uno de los estándares más utilizados para la descripción de APIs y, para ello, define un formato de descripción independiente a los fabricantes para los servicios compatibles con el formato REST [13].

3 Generación de servicios cuánticos

3.1 La especificación OpenAPI

La aceptación del nuevo sistema REST como método y protocolo de manipulación y de intercambio de datos entre los diferentes servicios web ha cambiado en gran medida el desarrollo de las mismas. Hoy en día, estos servicios suelen implementarse como servicios web RESTful (APIs web), por lo que existen pocas aplicaciones que actualmente no dispongan de una API REST para la creación de servicios [20]. De aquí surge la necesidad de estandarizar los servicios y de documentarlos para mantener la coherencia entre ellos [21]. OpenAPI es una de las alternativas más utilizadas entre los desarrolladores para realizar la definición e implementación de los servicios. Este estándar facilita el diseño de las APIs a partir de las diferentes herramientas que ofrece (Swagger Editor, OpenAPI Generator, etc.), proporcionando una estructura bien definida que cumple con el estándar y reduce considerablemente el tiempo de implementación de las APIs.

Para la implementación de un servicio clásico, un desarrollador necesita combinar dos aspectos principales. La lógica de negocio del servicio, que es específica de cada servicio, y la API del servicio. Utilizando la especificación OpenAPI se define la API del servicio, utilizando una interfaz estándar que es independiente del lenguaje para las API RESTful. Esto permite descubrir y comprender las características del servicio sin tener que acceder al código fuente o a la documentación, y definir el servicio y sus parámetros de entrada y salida. A partir de esta especificación, mediante un generador, se genera la estructura del código, por ejemplo en Python, en donde posteriormente se añade la lógica de negocio del servicio.

Por tanto, para abordar el estado actual de los servicios cuánticos, en este trabajo se ha decidido utilizar OpenAPI, de forma similar a como se está utilizando para la implementación de servicios clásicos. Para este fin, se utiliza un generador de código llamado OpenAPI Generator, creado por los propios desarrolladores del estándar OpenAPI. Sin embargo, esta herramienta está enfocada únicamente para la generación de servicios clásicos. Por ello, se propone una extensión de la especificación OpenAPI, incluyendo propiedades personalizadas, y una extensión del generador de forma que permita definir y generar código para aplicaciones cuánticas, e integrar el código de los circuitos cuánticos generados por compositores para este fin, como IBM Composer. De esta manera, basándose en la especificación OpenAPI proporcionada, junto con propiedades personalizadas, es posible generar el código del servidor que encapsule el código de los circuitos cuánticos. El lenguaje de los servicios generados es Python, al ser el lenguaje más utilizado en el desarrollo de software cuántico [22].

Para llevar a cabo la generación de servicios cuánticos, es necesario seguir un determinado proceso, el cual queda representado en la Figura 1. El primer paso a realizar es definir el circuito cuántico mediante la herramienta IBM Quantum Composer. Seguidamente, dicho código tiene que estar referenciado en el contrato YAML, mediante la URL donde esté alojado el código. Este contrato es un documento OpenAPI, que se ajusta a la especificación OpenAPI y es en sí mismo un objeto JSON con la especificación OpenAPI. Finalmente, el esqueleto del servicio cuántico se obtiene con el generador de código.

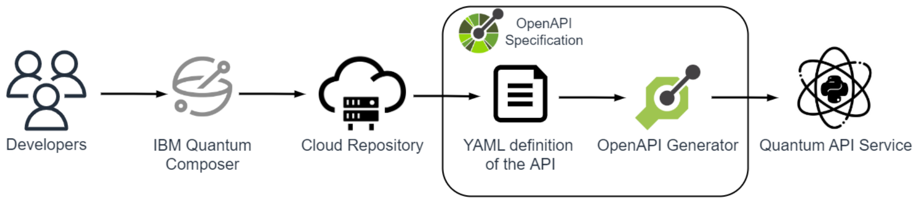


Fig. 1. Proceso de generación de servicios cuánticos con OpenAPI

3.2 Propuesta de creación de Servicios API Cuánticos

Pasando a describir en detalle la propuesta de creación de Servicios API Cuánticos, en primer lugar, es necesario especificar la ubicación del código del circuito cuántico generado con IBM Quantum Composer. Para nuestra prueba de concepto haremos uso del circuito cuántico corresponde al algoritmo de generación de números realmente aleatorios. Dicho circuito queda representado en la Figura 2, donde se puede observar que se necesita un registro cuántico de cinco Qubits para producir una secuencia de números aleatorios con valores de 0 a 31 y poner dichos Qubits en estado de superposición uniforme, mediante la inclusión de *puertas Hadamard*.

Para incluir dicho circuito en el servicio, es necesario 1) obtenerlo directamente del compositor o 2) alojar su código generado en un servicio en la nube, como puede ser un repositorio de *Github*. Hasta el momento y por lo que sabemos, no hay forma de obtener el código del circuito a partir de las APIs que ofrecen este tipo de compositores ni directamente desde sus URLs. IBM Quantum Composer y otros compositores sólo permiten la descarga del código generado y la posibilidad de ejecutarlo directamente en la propia plataforma. Por ello, se ha optado por la segunda opción, en la que el código descargado del compositor se sube a un repositorio en la nube.

Fig. 2. Circuito creado en IBM Quantum Composer para generar números aleatorios

Así las cosas, se propone extender el estándar para permitir la generación de aplicaciones cuánticas, en decir, para poder integrar el código generado por los compositores cuánticos en un servicio clásico.

```
/circuit/random:
  get:
    tags:
      - quantum_code
    summary: Get the circuit implementation for
             random numbers
    description: ''
    operationId: random_circuit
    parameters:
      - name: api_token
        in: query
        description: API Token
        required: true
        explode: false
        schema:
          type: string
    responses:
      '200':
        description: successful operation
      '405':
        description: Invalid execution
    x-quantumCode: 'https://raw.githubusercontent.com/
                   QuantumOpenAPI/random_number_qiskit.py'
```

Fig. 3. Ejemplo de la especificación de la API para el algoritmo de números aleatorios

Para este fin, se ha incluido en la definición del contrato de la API, en formato YAML, una propiedad personalizada (también llamada extensión de la especificación o extensión del proveedor) que se ha denominado *x-quantumCode*. Esto permite describir una función adicional que no está cubierta por la especificación estándar de OpenAPI. En este caso, el valor de la extensión es una primitiva, que contiene la URL donde se encuentra el código del circuito generado, como se puede ver en la Figura 3.

Para tener en cuenta esta nueva función adicional y poder generar el código del circuito encapsulado en el propio código de la API, dada la especificación OpenAPI anterior, lo siguiente es extender OpenAPI Generator. OpenAPI Generator es una herramienta web, creada por los propios desarrolladores de OpenAPI, que permite la generación de aplicaciones de servidor y clientes APIs. Para ello, cuenta con una serie de módulos y un conjunto de librerías que definen la generación de código para los diferentes lenguajes.

La propuesta de la versión extendida de la herramienta OpenAPI Generator, consiste en una nueva librería (*python-quantum*) basada en la librería Python existente para la creación de APIs con Flask[5].

Teniendo en cuenta este enfoque, se ha realizado una modificación de la clase principal de la librería mencionada para poder procesar el valor de la nueva extensión de la especificación y poder incluir el código del circuito y las librerías necesarias en el servicio. Además, para procesar los nuevos valores que se han añadido en la librería, se ha incluido una nueva lógica en las plantillas encargadas de generar el código del servicio.

Con todo ello, es posible generar la aplicación Flask que incluye el código del circuito generado por el IBM Quantum Composer indicando, en la llamada realizada al OpenAPI Generator, el lenguaje y el archivo YAML con la especificación OpenAPI, como se observa en la Figura 4.

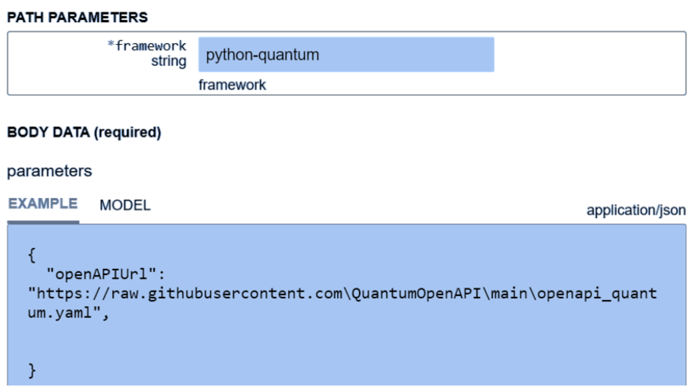


Fig. 4. Parámetros de llamada a OpenApi Generator para crear el Servicio API Cuántico

La Figura 5 refleja una de las clases generadas de la aplicación Flask del servicio cuántico. Concretamente, el algoritmo de generación de números aleatorios

[5] https://flask.palletsprojects.com/

que se encuentra encapsulado en un *endpoint* clásico de la API. Adicionalmente, las librerías necesarias para el funcionamiento del circuito del algoritmo cuántico, que genera IBM Composer, también son importadas dentro del código.

Este servicio Flask generado puede desplegarse en un ordenador clásico y proporciona una forma sencilla de incluir algoritmos cuánticos en una solución compleja orientada a servicios. La manera de acceder a dichos algoritmos es mediante peticiones REST clásicas, es decir, invocando los *endpoints* donde se haya desplegado el servicio mediante los métodos HTTP.

La especificación OpenAPI del algoritmo utilizado como prueba de concepto de generación de números aleatorios y el correspondiente código del Servicio API Cuántico generado se encuentran disponibles en el repositorio de *GitHub*[6].

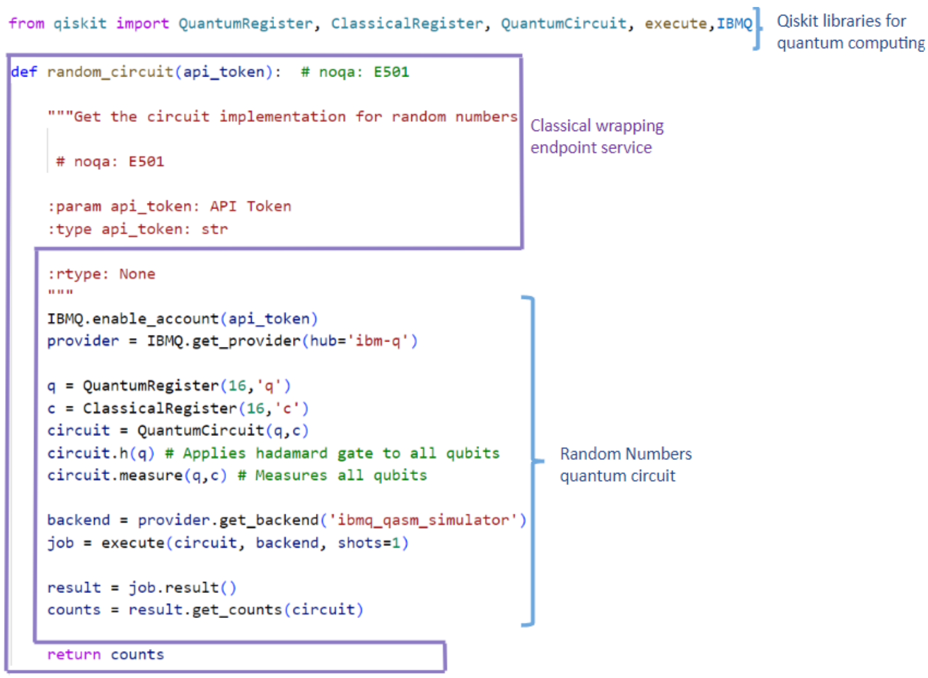


Fig. 5. Fragmento de servicio API generado que encapsula el circuito cuántico

4 Conclusiones

Este trabajo ha permitido presentar algunas de las limitaciones actuales en la construcción y el uso de los servicios cuánticos, viendo la necesidad de llevar los beneficios de la computación orientada a servicios al mundo cuántico. Además de que los desarrolladores de aplicaciones de servicios están más familiarizados

[6] https://github.com/JaimeAlvaradoValiente/QuantumOpenAPI.git

con las herramientas de abstracción de alto nivel, que simplifican el proceso de desarrollo y despliegue.

Con este fin, se ha ampliado la especificación OpenAPI para poder definir servicios cuánticos y poder generar el código correspondiente de manera que permita una mayor coherencia y abstracción a la hora del desarrollo de sistemas híbridos clásico-cuánticos.

Para poder realizar una aproximación a la servitización de servicios cuánticos y poder verificar la viabilidad de la propuesta, se ha realizado la definición e implementación de una API de Flask que encapsula el circuito cuántico correspondiente al algoritmo de generación de números aleatorios. En este sentido, se ha utilizado la extensión realizada sobre la especificación OpenAPI y su generador de código para poder servitizar el servicio y encapsular el circuito cuántico.

Esta modificación de la herramienta de generación de código tiene margen de mejora, como por ejemplo lograr un mayor nivel de abstracción de cara al desarrollador, o la integración con los demás proveedores de máquinas cuánticas que existen en el mercado. De esta forma, se deben realizar esfuerzos en la integración de los sistemas híbridos clásico-cuánticos, hasta poder ofrecer un ecosistema de desarrollo similar al que podemos encontrar para los servicios clásicos.

Agradecimientos

Este trabajo ha sido parcialmente financiado por el proyecto 0499_4IE_PLUS _4_E (Interreg V-A España-Portugal 2014-2020); por el Ministerio de Ciencia, Innovación y Universidades (el proyecto RTI 2018-094591-B-I00 y la ayuda FPU19 / 03965); la Consejería de Economía e Infraestrutura de la Junta de Extremadura (GR18112, IB18030) cofinanciado por el Fondo Europeo de Desarrollo Regional (FEDER).

Referencias

1. M. J. Klein, "Max planck and the beginnings of the quantum theory," *Archive for History of Exact Sciences*, vol. 1, no. 5, pp. 459–479, 1961.
2. E. National Academies of Sciences, Medicine *et al.*, *Quantum computing: progress and prospects.* National Academies Press, 2019.
3. E. R. MacQuarrie, C. Simon, S. Simmons, and E. Maine, "The emerging commercial landscape of quantum computing," *Nature Reviews Physics*, vol. 2, no. 11, pp. 596–598, 2020.
4. J. Zhao, "Quantum software engineering: Landscapes and horizons," 2020. [Online]. Available: https://arxiv.org/abs/2007.07047
5. Shubham, P. Sajwan, and N. Jayapandian, "Challenges and opportunities: Quantum computing in machine learning," in *2019 Third International conference on I-SMAC*, 2019, pp. 598–602.
6. S. Aaronson, "BQP and the Polynomial Hierarchy," *Proceedings of the Annual ACM Symposium on Theory of Computing*, pp. 141–150, oct 2009.

7. F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, R. Barends, R. Biswas, S. Boixo, F. G. Brandao, D. A. Buell *et al.*, "Quantum supremacy using a programmable superconducting processor," *Nature*, vol. 574, no. 7779, pp. 505–510, 2019.
8. J. M. Garcia-Alonso, J. Rojo, D. Valencia, E. Moguel, J. Berrocal, and J. M. Murillo, "Quantum software as a service through a quantum api gateway," *IEEE Internet Computing*, 2021.
9. A. McCaskey, E. Dumitrescu, D. Liakh, and T. Humble, "Hybrid programming for near-term quantum computing systems," in *2018 IEEE International Conference on Rebooting Computing (ICRC)*. IEEE, 2018, pp. 1–12.
10. M. Rahaman and M. M. Islam, "A review on progress and problems of quantum computing as a service (qcaas) in the perspective of cloud computing," *Global Journal of Computer Science and Technology*, 2015.
11. J. Rojo, D. Valencia, J. Berrocal, E. Moguel, J. M. García-Alonso, and J. M. Murillo, "Trials and tribulations of developing hybrid quantum-classical microservices systems," *ArXiv*, vol. abs/2105.04421, 2021.
12. C. A. Pérez-Delgado and H. G. Perez-Gonzalez, "Towards a quantum software modeling language," in *Proceedings of the IEEE/ACM 42nd International Conference on Software Engineering Workshops*, 2020, pp. 442–444.
13. S. Schwichtenberg, C. Gerth, and G. Engels, "From open api to semantic specifications and code adapters," in *2017 IEEE International Conference on Web Services (ICWS)*. IEEE, 2017, pp. 484–491.
14. X. Ma, X. Yuan, Z. Cao, B. Qi, and Z. Zhang, "Quantum random number generation," *npj Quantum Information*, vol. 2, no. 1, pp. 1–9, 2016.
15. M. Piattini, G. Peterssen, and R. Pérez-Castillo, "Quantum computing: A new software engineering golden age," *SIGSOFT Softw. Eng. Notes*, vol. 45, no. 3, p. 12–14, Jul. 2020. [Online]. Available: https://doi.org/10.1145/3402127.3402131
16. M. Piattini, G. Peterssen, R. Pérez-Castillo, J. L. Hevia, M. A. Serrano, G. Hernández, I. G. R. de Guzmán, C. A. Paradela, M. Polo, E. Murina *et al.*, "The talavera manifesto for quantum software engineering and programming." in *QANSWER*, 2020, pp. 1–5.
17. P. E. Z. Junior and V. V. de Camargo, "A systematic mapping on quantum software development in the context of software engineering," *arXiv preprint arXiv:2106.00926*, 2021.
18. E. Moguel, J. Rojo, D. Valencia, J. Berrocal, J. Garcia-Alonso, and J. M. Murillo, "Quantum service-oriented computing: current landscape and challenges," *Software Quality Journal 2022*, pp. 1–20, 4 2022. [Online]. Available: https://link.springer.com/article/10.1007/s11219-022-09589-y
19. I. Kumara, W.-J. V. D. Heuvel, and D. A. Tamburri, "QSOC: Quantum Service-Oriented Computing," pp. 52–63, may 2021. [Online]. Available: https://arxiv.org/abs/2105.01374v1
20. A. Soni and V. Ranga, "Api features individualizing of web services: Rest and soap," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 9, pp. 664–671, 2019.
21. A. Karavisileiou, N. Mainas, and E. G. Petrakis, "Ontology for openapi rest services descriptions," in *2020 IEEE 32nd International Conference on Tools with Artificial Intelligence (ICTAI)*. IEEE, 2020, pp. 35–40.
22. V. Silva, *Practical quantum computing for developers: programming quantum rigs in the cloud using Python, quantum assembly language and IBM QExperience*. Apress, 2018.

Appendix R

Quantum Service-Oriented Architectures: From Hybrid Classical Approaches to Future Stand-Alone Solutions

Authors: *David Valencia, Enrique Moguel, Javier Rojo, Javier Berrocal, Jose Garcia-Alonso, Juan Manuel Murillo.*

Publication type: *Book chapter.*

Book: *Quantum Software Engineering.*

Year of publication: *2022.*

DOI: *10.1007/978-3-031-05324-5_8*

Chapter 8
Quantum Service-Oriented Architectures: From Hybrid Classical Approaches to Future Stand-Alone Solutions

David Valencia, Enrique Moguel, Javier Rojo, Javier Berrocal, Jose Garcia-Alonso, and Juan M. Murillo

8.1 Introduction

During the last decades, quantum computing [1] has been a very promising and relevant research field, which encompasses not only computer science but also other scientific fields such as information theory or quantum physics. In later years, one can say that the development of quantum computers has reached a turning point with the advent of noisy intermediate-scale quantum (NISQ) computers [2], with tens of qubits, which allow to tap on tasks that outperform capabilities of classical computers.

The latter, along with confluence of other socioeconomic circumstances, are producing an ever-growing interest on quantum computing from commercial companies [3]. An example of the actual situation and possible future quantum commercial landscape can be found on the fact that several major computing corporations, such as IBM,[1] are starting to build their own quantum computers with the idea of offering them to end users on a pay-per-use model. Each of the particular solutions proposed by enterprises is accompanied by their own quantum programming languages which are laying the basis of future development of quantum services and software engineering.

Although a promising quantum computing era leading the future of computing engineering is more clearly devised each day, the current state of art of quantum computing is more focused on the integration of quantum computers with classical ones, which has been coined as hybrid classical-quantum computing [4, 5]. With this outlook in mind, a natural way of exploiting the collaborative coexistence and

[1] https://www.ibm.com/quantum-computing

D. Valencia · E. Moguel (✉) · J. Rojo · J. Berrocal · J. Garcia-Alonso · J. M. Murillo
University of Extremadura, Cáceres, Spain
e-mail: davaleco@unex.es; enrique@unex.es; javirojo@unex.es; jberolm@unex.es; jgaralo@unex.es; juanmamu@unex.es

M. A. Serrano et al. (eds.), *Quantum Software Engineering*,
https://doi.org/10.1007/978-3-031-05324-5_8

pay-per-use perspective lies in the principles of service computing and engineering; in fact, many of the research done and efforts of companies lean on the usage of quantum infrastructures to allow consumption of quantum infrastructure as a service with an approximation similar of usage of classical computing resources, i.e., IBM Quantum Computing or Amazon Braket[2] in what can be coined as a Quantum Service-Oriented Computing (QSOC) strategy. The underlying idea of the solutions proposed by companies is based on the facts that quantum computers are still very hard to operate and very expensive to own.

Again, all the aforementioned architectures are extremely aligned with another interesting and successful approach during the last decades, the microservices architectural pattern [6], in which complex systems are devised as distributed microservices, each of them being an independent process that interacts with the rest through consumption of services, appearing to the end users as a whole virtual computer. In this way, incorporating quantum computers to this paradigm will allow to tackle on both classical and quantum problems from a microservices point of view. Thus, the first step on this line of work must focus on the conversion from quantum software to microservices to be integrated on existing architectures.

From a microservice standpoint, the integration of quantum software should not be very different from classical microservices, in a way that it can be considered an independent process with the ability to interact with the rest of the system through consumption of services, and the underlying hardware is irrelevant. Nonetheless, current state of the art of quantum computing proves the latter to be a false assumption, forcing the necessity of specific approaches to generate hybrid microservices architectures. In particular, executing a quantum algorithm as a microservice is feasible with it being wrapped by a classical service, by means of quantum software development kits, although with some limitations imposed by current state of the art of quantum computing. First and foremost, quantum algorithms invocation and execution are extremely coupled with underlying hardware, leading to vendor locking. Secondly, results produced, mainly due to the probability distribution over possible quantum states [7], by quantum algorithms differ from classical solutions, further increasing the coupling with the quantum processor used. This also exposes another problem associated with NISQ computers, which is related to existing noise, leading to results subject to errors usually dependent on the specific quantum computer and qubit topology. Last but not least, related with quantum system collapse, one finds that it is not possible to obtain intermediate verification of results, further affecting and reducing service orchestration.

From all of the above, it is clear that integration of classical-quantum services is a very interesting and promising approach which continues the road laid down by cloud computing, but invoking a quantum microservice in an agnostic way is not possible, which violates all principles of service-oriented computing, producing that all of the advantages of this paradigm are lost, specifically those related to software quality x-abilities, i.e., composability, maintainability, reusability, and so on. To

[2] http://aws.amazon.com/braket

cope with this problem, some of the techniques and methodologies of classical service engineering must be translated to quantum service engineering domain, and several new ones must be researched and proposed.

The chapter is organized as follows: first, traditional microservices and their characteristics are explored; in the next section, an actual commercial proposal for development and execution of quantum software similarly to cloud computing is explored using two well-known problems solved with different quantum computing approaches; in Sect. 8.4, a proposal of a quantum service architecture is shown to try to cope with problems detected in the previous section; finally, in the last sections, the conclusion and related and future works are showcased.

8.2 Background

In order to address the integration of quantum and classical microservices under a single architecture, it is necessary to understand how current classical microservices work. This section does not pretend to be an exhaustive review of microservices, as there is a wealth of literature on this topic [8, 9]. It is simply intended to present an overview of how microservices work and to discuss those architectural and design patterns that will need to be adapted to support quantum microservices.

Microservices architecture is an application architectural style in which an application is composed of many discrete, network-connected components. These components are called microservices [10]. The microservices architectural style can be considered an evolution of the SOA (services-oriented architecture) architectural style [11]. The main differences between the two of them lie on the fact that while applications built with SOA services tended to focus on technical integration issues, and the level of services implemented were often very larger-grained technical APIs, the microservices approach remains focused on implementing clear business capabilities through fine-grained business APIs.

But aside from service design issues, perhaps the biggest difference is the deployment style. For many years, applications have been packaged monolithically, that is, a team of developers would build a large application that did everything needed for a business need. Once built, that application was deployed multiple times to an application server. In contrast, in the microservices architectural style, several smaller applications are built and packaged independently, each implementing only part of the whole.

In general, SOA and microservices architecture do not compete. Both approaches can coexist, each bringing its own advantages. In particular, those that make microservices architecture desirable are the following:

- The services are not integrated into the main system (loosely coupled), so they are easier to develop and deploy. They can have independent scalability, and failures can be isolated to a particular microservice, rather than a section or operation of the application.

- Radical changes in the technology stack are not necessary, but the most appropriate technology can be used for each service independently of the technologies used in the rest of microservices.
- Microservices are, in general, easier to maintain and test since they are small pieces of software doing only one specific thing.
- From the development point of view, it is easier to get in and start being productive, as the developers deal with the operation of several small services instead of a complex one. In this way, the integration of microservices development with DevOps and Agile methodologies is easier.

On the other side, relaying on a microservices architecture has the following disadvantages associated with it:

- The complexity of microservices systems tends to be higher than their monolithic counterparts. Additional to the systems functionalities, the coordination between the different microservices has to be addressed. This usually involves different communications protocol and synchronization mechanisms that increase the overall system complexity.
- Similarly, deploying and operating a microservices system is much more complicated than deploying a monolith system. The management and maintenance of the different microservices requires greater coordination and effort from the operations team.
- A microservices system tends to require higher computing capabilities than a monolith. Although each microservice can be optimized for its tasks, its deployment requires its own container, dependencies, etc. that are replicated for each service. The aggregated needs of the microservices are usually greater than that of an alternative monolith.

In any case, the development of microservices, like any other software artefact, is based on software engineering development processes. Due to the microservices architecture success, in the software development industry as well as in academia, there are a great number of techniques, methodologies, and tools to help developers create this type of system.

Some of the most relevant are the decomposition patterns that help determine which parts of the system are assigned to each microservice. Also, specifications like Open API [12] help developers standardize their endpoints and provide code generation tools that facilitate the work of developers.

Once a microservice application has been developed, it also has to be deployed and maintained. These tasks are covered under the DevOps term [13, 14] and include aspects related to the integration, testing, administration, monitoring, etc. of microservices.

For traditional systems, the first step in operating a microservices system is the deployment. Many of the advantages provided by this architecture, such as the scalability, are possible, thanks to the deployment strategy followed. Therefore, when deploying microservices, it is necessary to take into account aspects such as where each service is going to be deployed (several services on the same host machine or each service in a different machine), the type of deployment (serverless, containers, VMS, etc.), orchestration, activity logging, etc.

To hide this complexity for the microservices consumers, the API Gateway integration pattern is used. An API Gateway is the single-entry point for any microservice call. It can work as a proxy service to route a request to the microservice in question. It can also aggregate the results to send back to the consumer or even create a fine-grained API for each specific type of client. It also can take care of additional aspects like authentication/authorization. All this allows developers of microservices systems to handle multiple calls to multiple microservices from different channels, to handle different protocols, and to provide response in different formats to different clients.

Once the services are deployed, all the issues related to management and maintenance must also be considered. Considering communications between the different services, transaction management, maintaining data consistency, monitoring of running services, security, testing and many other aspects.

As mentioned above, all these aspects have been studied for researchers and practitioners, and good practices have been proposed and adopted to improve the development of microservices. However, as far as the authors know, there are no studies on which of these practices can be adapted to the creation of quantum microservices or which need to be replaced by more specific alternatives.

8.3 Current Status of Quantum Microservices: The Amazon Braket Case Study

In the present section, a brief review of the current leading technology solutions is presented in order to ease understanding and evaluation of underlying hardware supporting quantum microservices, along with their strengths and drawbacks.

8.3.1 Main Quantum Computing Approaches

As indicated before, we are facing a new era of quantum computing, led mainly by the noisy intermediate-scale quantum (NISQ) computers, in whose one may find reminiscences of beginning of the transistor era of classical computing, when the evolution started to grow exponentially, finally leading to the great breakthrough that enabled the current development of information systems. This evolution has been a challenging process that, among other advances, has motivated the development of software engineering as it is today. Researchers and industry must prepare to face a similar process in the coming years, now facing the development of quantum computing.

Current commercial quantum computing hardware and computers can be roughly classified in two categories: quantum gate arrays and adiabatic quantum computers. In the first category, we can find proposals of commercial quantum computers of companies such as IBM's with their Quantum System One[3] with more than 20 qubits and Rigetti's Aspen-9[4] with more than 30 qubits. On the other category, their main exponent is D-Wave's Advantage[5] architecture, with more than 5000 qubits.

Most current information systems are supported by cloud computing at any level (IaaS, PaaS, or SaaS). Today's quantum computers are no different in this regard and are already available in the cloud under pay per use. One example of this can be found on Amazon's bracket. Amazon defines Braket as a fully managed quantum computing service. Specifically, Braket provides a development environment to build quantum algorithms, test them on quantum circuit simulators, and run them on different quantum hardware technologies; it is a strategy allowing Amazon to further expand their position, as the global leader regarding cloud computing and services technologies through AWS, into the quantum computing area. Braket offers both adiabatic and gate array-based quantum computers as underlying hardware to execute the codes developed in their platform. At the moment of writing this chapter, Braket supports three different quantum computer simulators and real quantum computers from three different hardware vendors: Rigetti and IonQ (gate-based) and D-Wave (quantum annealing).

The approach followed by Amazon Braket tries to cope with the first choice a developer must make when faced with building a quantum program, that is: *Should we exploit both mainstream quantum possibilities (adiabatic and gate-based) or work only with one type of architecture? In that case, which one?* The aim of Braket is to provide a higher abstraction level so users (potentially developers) are agnostic of the underlying hardware and focused on the problem requirements. Additionally, flexibility and scalability are also benefited. Nonetheless, due to the relative novelty of the quantum proposals along with the particularities of quantum computing, getting all the advantages of the new abstraction level is still more of a wish than a reality. To illustrate this, this chapter will evaluate the complexity and shortcomings of developing two quantum algorithms as services in Amazon Braket, one especially suitable for quantum gate-based architectures (prime factoring) and a second one suitable for quantum annealing (traveling salesperson problem).

8.3.1.1 Prime Factoring

Prime factorization is a particular application of integer factorization, a fundamental problem in number theory that is computationally hard, but it is not believed to belong to the NP-hard class of problems [15]. Nonetheless, it is a problem that has

[3] https://www.research.ibm.com/quantum-computing/system-one/

[4] https://www.rigetti.com/

[5] https://www.dwavesys.com/quantum-computing

been used as a basic hardness assumption for cryptographic algorithms, such as the famous RSA algorithm. Thus, integer factorization and identification of new methods to address this task acquire an important role in information security.

The problem proposed is basically to try to decompose a non-prime integer number in nontrivial divisors, as indicated in Eq. (8.1), where N denotes the non-prime integer and p and q are the nontrivial (prime) divisors:

$$N = pq \tag{8.1}$$

There are multiple proposals and algorithms for the solution of this problem, being the most famous Shor's algorithm [7]. This algorithm is normally described in terms of quantum gates and circuits, suitable for development and execution on machines such as IBM's Q computing chip [16], but when considering other approaches on quantum computing, such as Adiabatic Quantum Computing based on concepts such as quantum annealing, Shor's algorithm implementation is not direct. Nonetheless, other algorithms have been proposed for prime factoring, such is the case of the algorithm proposed by Wang et al. in [17]. In particular, in the studies conducted on this paper, these will be the algorithms proposed for integer factorization: Shor's algorithms for quantum machines programmed with quantum circuits and gates, such as Rigetti's [18] and IonQ's [19], and integer factorization based on quantum annealing for adiabatic quantum machines such as D-Wave's [20]. The selection of these algorithms is done without losing generality, in fact as Shor's algorithm is a very well-known study example for gate-based quantum computers, whereas the algorithm proposed for quantum annealing is selected because clearly shows the intricacies of specifying a problem in a QUBO form. Particularly, in Fig. 8.1, a part of the code generated for the factorization of number 21 is shown.

However, when working with quantum annealing, the problem must be reformulated to take the form of a QUBO or Ising, defining it by means of graphs with valued vertex and valued links between these vertices where vertex represents variables and links represent dual relationships between variables. Any higher-order relationship such as those found on terms involving three or more variables must be mathematically transformed to simpler two-variable-related terms. This task can be of great complexity due to the necessity of ample and profound comprehension of the problem and dexterity on mathematical knowledge and tools. To illustrate this, in Fig. 8.2 are shown the values of the weights of the nodes along with the edges between nodes for the factorization of 21. The steps to call the execution on D-Wave's quantum computer using Amazon Braket are also included.

8.3.1.2 Traveling Salesperson Problem (TSP)

Contrary to prime factoring, this is a recognized example in the class of NP-Class problems [21], which can be categorized as an optimization problem. In the traditional definition of the problem, there exists a traveling salesperson that must visit all cities inside a route, minimizing the traveled distance. Thus, in the classical

```python
def period(a,N, device="LocalSimulator"):
    global Ran_Quantum_period_finding
    Ran_Quantum_period_finding = 1
    num_qubits = 5
    C_reg = [0,0,0]
    quantum_circuit = Circuit()

    quantum_circuit.x(0)
    quantum_circuit.h(4)
    quantum_circuit.h(4)
#   quantum_circuit.measure(4,C_reg[0])
#   # Reinitialize to |0>
#   quantum_circuit.reset(4)

    quantum_circuit.h(4)
    for k in range(2):
        cmod(quantum_circuit,a)
    if C_reg[0] == 1:
        quantum_circuit.rz(4,pi/2.0)
    quantum_circuit.h(4)

    quantum_circuit.h(4)
    cmod(quantum_circuit,a)
    if C_reg[1] == 1 :
        quantum_circuit.rz(4,pi/2.0)
    if C_reg[0] == 1 :
        quantum_circuit.rz(4,pi/2.0)
    quantum_circuit.h(4)

    result = run(quantum_circuit, device)
    counts = result.measurement_counts
```

Fig. 8.1 Circuit for Shor's algorithm

```python
dwave_sampler = BraketDWaveSampler(s3_folder,'arn:aws:braket:::device/qpu/d-wave/DW_2000Q_6')
dw_sampler_embedding=EmbeddingComposite(dwave_sampler)
h={'s1': 580, 's2': 420, 's3': 144, 's4': 128}
J={('s1','s2'): 152, ('s1','s3'): -144, ('s1','s4'): -512, ('s2','s3'): 16,('s2','s4'):  -512, ('s3','s4'): 128}
sampleset=dw_sampler_embedding.sample_ising(h,J,num_reads=100)
```

Fig. 8.2 D-Wave's invocation for the factoring of 21

definition of the problem, there exist cities, usually described as nodes, and roads connecting those cities, which can be considered as links between these nodes, each with a weight indicating the distance. An example of this problem is shown in Fig. 8.3.

The main difficulty of these kinds of problems relates to the increment of possible solutions with the increase of the problem size, i.e., with 5 cities, there exist 12 possible routes, whereas for 25 cities, the number of routes grows to 3.1×10^{23}. Furthermore, this particular problem has been expanded into more realistic and complex formulations, usually in the forms of restrictions, such as the case of the (Capacitated) Vehicle Routing Problem [22] or the case of TSP with Time Windows [23].

Resolving this problem by classical computing methods is not always optimal, and several methods, with their limitations, have been developed over the years as replacement to brute force solutions on these optimization problems. In recent years,

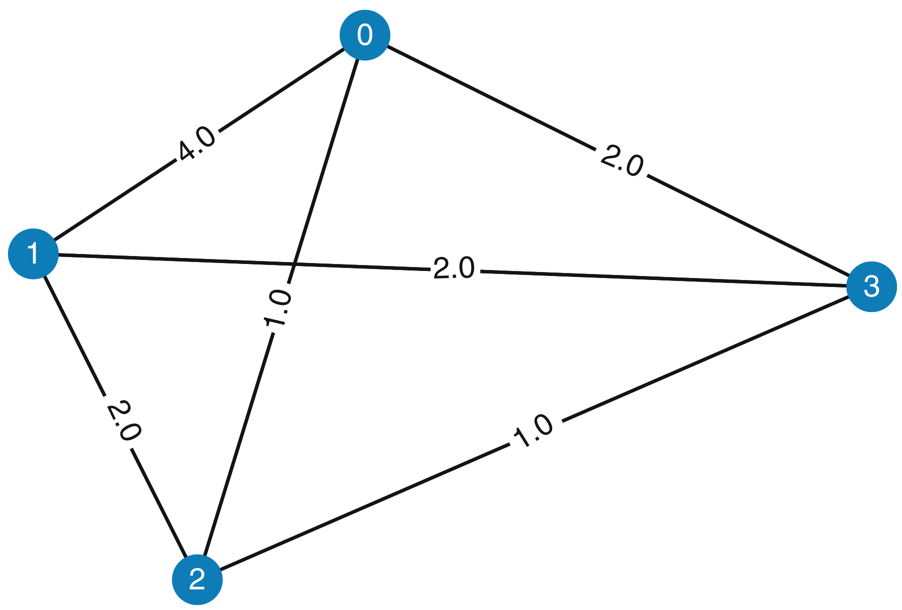


Fig. 8.3 Example of a graph defining a TSP with four cities and the roads interconnecting them

due to the expansion of quantum computing, researchers began to develop quantum algorithms that solve these problems: both for the perspective of adiabatic quantum computing [24] and for the perspective of gate-based quantum computing [25, 26].

To solve the problem in Amazon Braket, the code described in Fig. 8.4 has been developed to work with quantum gate-based computers.

On the other hand, using quantum annealing to solve this problem is quite straightforward, only needing to invoke a call to function, which is shown in Fig. 8.5.

8.3.2 Limitations of Getting Service-Oriented Computing Benefits in Quantum Computing Environments

Taking as a starting point the problems described in the previous section and the description of their solutions in each quantum computational model, the aim of this section is to highlight the difficulties encountered when trying to provide agnostic implementations of the underlying computational model using Amazon Braket.

More specifically, the experiments carried out allow us to conclude that there is some roughness, limitations, and problems that arise when a quantum piece of software is expected to be provided as a service. They are mainly related to the fact that, using current proposals to integrate quantum technologies such as Amazon Braket, the benefits of service-oriented computing are lost.

First and foremost is the impossibility of abstracting the service from the underlying quantum computational model. The consequence is that both the service developer and the users of the service are left with the problem of vendor locking.

```
def circuit(eigenstate):

    if len(eigenstate)!=n_eigenvector:
        return None

    circuit = Circuit()

    for i in range(0, n_eigenvector):
        if eigenstate[i]=="1":
            circuit.x(n_anc+i)

    for i in range(n_anc):
        circuit.h(i)

    cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,1)
    cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,1)
    cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,1)
    cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,1)
    for i in range(2):
        cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,2)
        cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,2)
        cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,2)
        cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,2)
    for i in range(4):
        cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,3)
        cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,3)
        cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,3)
        cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,3)
    for i in range(8):
        cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,4)
        cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,4)
        cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,4)
        cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,4)
    for i in range(16):
        cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,5)
        cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,5)
        cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,5)
        cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,5)
    for i in range(32):
        cont_U(circuit,0,math.pi/2,math.pi/8,math.pi/4,0,6)
        cont_U(circuit,math.pi/2,0,math.pi/4,math.pi/4,2,6)
        cont_U(circuit,math.pi/8,math.pi/4,0,math.pi/8,4,6)
        cont_U(circuit,math.pi/4,math.pi/4,math.pi/8,0,6,6)

    qft_dagger(circuit,6)

    machine = LocalSimulator()
    result = machine.run(circuit, shots=10000).result()
    counts = result.measurement_counts

    return counts
```

Fig. 8.4 Solution of the traveling salesperson problem implemented for gate-based quantum computers

In particular, because the formulation of the solution for a given problem is completely different depending on the underlying quantum computational model, each implementation for a given solution requires different number and type of parameters depending on the underlying quantum machine. The difficulties are even

```
def TSP_annealing(G):

    dw_sampler = BraketDWaveSampler(s3_folder,
                                    'arn:aws:braket:::device/qpu/d-wave/DW_2000Q_6')
    dw_sampler = EmbeddingComposite(dw_sampler)

    n_shots = 1000
    start_point = 0
    best_distance = sum(weights.values())
    best_route = [None]*len(G)

    for l in lagrange_list:
        print('Running quantum annealing for TSP with Lagrange parameter=', l)
        route = traveling_salesperson(G, dw_sampler, lagrange=l,
                                      start=start_point, num_reads=n_shots,
                                      answer_mode="histogram")

        total_distance, distance_with_return = get_distance(route, data)

        if distance_with_return < best_distance:
            best_distance = distance_with_return
            best_route = route

    return best_route, best_distance
```

Fig. 8.5 Solution of the traveling salesperson problem using quantum annealing

greater when facing solutions to problems whose formulation depends on factors such as the size of the problem. This is the case of the solution provided for prime factorization on an adiabatic architecture. As mentioned, that solution is formulated using a QUBO or Ising (Fig. 8.2). Transforming the formulation to a two-variable term formulation is a task whose complexity increases with the size of the number to be factorized, mainly due to the introduction of auxiliary terms to simplify high-order terms. The resulting number of parameters (two-variable terms) also depends on this size.

Another limitation lies in the number of qubits available especially in the case of gate-based systems. This fact directly limits the ability to run the solutions. For example, in the case of the TSP shown in Fig. 8.3, when considering the Gate-based solution, the number of qubits amounts to 14 (8 for eigenstates + 6 for phase), so this small problem exceeds the number of qubits available (11 qubits) executed on the IonQ hardware. This shows not only the limited power of the current hardware but also the need for mechanisms to be included in quantum service computing to determine the number of qubits needed so the executions can be launched in appropriated powerful enough quantum computers. Due to the nature of quantum algorithms for the different architectures, there is no trivial way obtain this number. This will be a key question in developing quantum services execution schedulers. However, this is not the only feature to have into account. There are many others with implications in several other aspects of the service, such as the case of response and awaiting time. Due to the nature of quantum computations making use of quantum entanglement to explore all solutions at the same time, it is not possible to query the system because it will be forced to collapse. Thus, it is not possible to initially estimate response times without affecting the outcome of the algorithm and can only base it on statistical calculations from previous execution times.

Finally, one of the biggest hurdles is related to the inherent nature of quantum computing and their underlying physical phenomena that serve as base for the quantum architecture. It is the case of ion traps or quantum chips. Due to the problems that arise due to the characteristics of current quantum computers, mainly noise in the qubits state, the experiments must be conducted several times to be statistically consistent. Along with the latter, depending on the architecture executing the quantum code, one must work with a panoply of solutions ranging from energy levels of solutions to "simple" probabilities and cases. This goes directly against the agnostic nature of services, in which the underlying technology should be irrelevant for the service consumer. For a real quantum service technology, the responsibility of performing the different executions to get a consistent result cannot be delegated in the client nor the customer who only wants to use a technology to get a correct result, at least within a given margin of error, and with an economic cost known in advance. How the number of shots required is estimated will have a direct impact in the cost of the service executions. This reveals some issues, related with service quality and costs, which still have to be addressed by quantum services engineering.

8.4 Directions for a Future QSOC

Taking into account the examples depicted in the previous section, it is clear that using classical SOC and microservices principles to develop hybrid quantum-classical information systems is still far from being possible. Thus, some methodologies and techniques may have to be imported directly from the classical world to the quantum world, while many others will need to be adapted, and some new ones will have to be introduced.

A good starting point is to define a set of good practices that provides support to the development and operation of quantum microservices. This is just the purpose of Fig. 8.6. It proposes several steps that should be taken into account to create quantum software that can be consumed as a microservice. The proposed steps are based on current microservices and quantum technologies and try to exploit the benefits of both worlds.

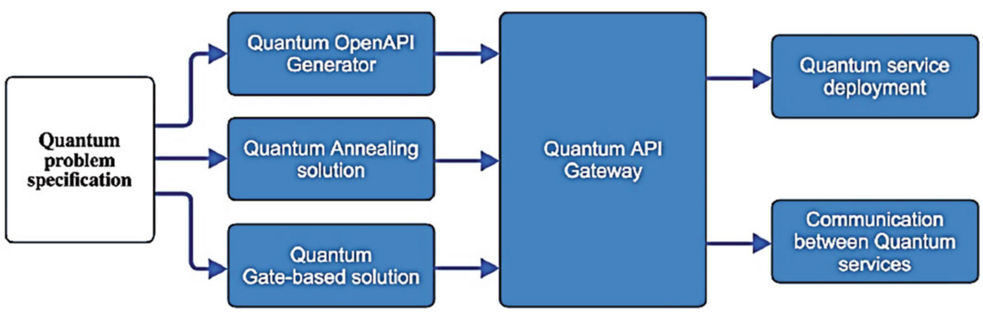


Fig. 8.6 Quantum services recommended practices

The first step to create a quantum microservice is the specification of the quantum problem to be addressed. This step is very tightly related with the abovementioned decomposition patterns of classical microservices. A microservice should focus on implementing a single business capability. In the specific case of quantum services, and given the current state of quantum hardware, any part of the problem that can be solved by traditional services should be implemented as such. Only specific problems that benefit from running on a quantum computer should be implemented as quantum algorithms.

Once this decomposition is done, the quantum services functionality should be defined abstracting as many details as possible from the underlying quantum hardware. For traditional services, one of the most extended mechanisms to perform this task is the OpenAPI Specification. It defines a standard, language-agnostic interface to RESTful APIs which allows both humans and computers to discover and understand the capabilities of services without access to source code or documentation. The same standard can be used for quantum services, although some modifications may be needed to included specific quantum aspects such as the number of qubits needed to run the service given a certain input or the number or shots to be executed.

From the OpenAPI specification of traditional services, a code generation tool is able to generate API client libraries, server stubs, documentation, and configuration automatically for dozens of programming languages. This tool can be extended to support code generation for quantum services. This would abstract quantum microservices developers from most of the specific details of the supported quantum hardware and gain the support of the classical service community that are already used to the OpenAPI ecosystem.

Although such quantum code generation tools can abstract many implementation details, a quantum algorithm still needs to be developed to perform the microservice computation. A quantum annealing solution, or a quantum gate-based solution (or both), should be provided as the body of the generated quantum service.

Another interesting area to explore is related to the deployment of services. From this point of view, the situation is very different to traditional services. To the authors' knowledge, actually, it is not possible to deploy services on quantum machines; thus, the quantum software to be executed is deployed upon execution, leading to a redeployment with each invocation. This implies an increase in the computational resources needed to execute quantum microservices. Each time a quantum microservice is consumed, it has to be deployed first. However, this disadvantage can be turned into an advantage. A Quantum API Gateway should be able to perform all the task that a traditional API Gateway performs and, at the same time, apply a heuristic to decide the best quantum hardware in which to deploy the service at each time. This heuristic could take into account the available quantum computers in which the service can be run, the number of qubits needed, the cost of running the service on each quantum computers, and other similar aspects. From this information, the optimal hardware can be chosen for each user on real time, providing a greater flexibility than traditional services where the deployment is only performed one time.

Another necessary step is involved in the communication between traditional microservices and quantum microservices. For this particular problem, one approximation could be following an approach similar to how many traditional microservices manage communications, using queues for the messages. However, the collapse of the quantum systems should be taken into account. Once the quantum algorithm that runs as the body of a quantum microservice has started is execution, it will not be possible to consult its state without collapsing the system and, almost certainly, invalidating the execution. Therefore, communications between quantum services should be managed before or after the quantum core of the service is executing and communication systems should be adapted to this behavior. The Quantum API Gateway can also help coordinate these aspects each time a quantum service is deployed.

From all the above, it is clear that there are two key elements needed in order to be able to efficiently integrate hybrid quantum computing services, the specification of the problem and the Quantum API Gateway. Both allow developers to mitigate the problems of vendor lock-in and impossibility of deployment on quantum computers. Additionally, a code generation tool can also help bridge the gap between them in a way that is familiar to most services developers. Thus, we feel that the focus of quantum microservices engineering should be in designing and developing these set of proposed good practices in order to translate the benefits of traditional microservices to hybrid quantum microservices.

8.5 Related Works

To date, works that focus on quantum microservices or hybrid microservices architectures are still sparse, and this is because quantum software engineering is a young discipline. However, some researchers are starting to focus on this and related topics.

Already there are works that begin to explore the research opportunities of quantum services and the potential of quantum services in the cloud [27]. In this paper, researchers from different studies emphasize the problems encountered during their research in this area. In particular, it includes the problems caused by the need for different implementations of the same quantum algorithms for different hardware vendors or the problems in deploying quantum services on quantum computers.

As previously mentioned, in [28], the researchers further explore the deployment of quantum services through an extension of TOSCA for quantum software deployment. This proposal shares some similarities with the work proposed in this book chapter. Because quantum applications must be deployed again for each invocation, a classical computer is needed to host and deploy these applications. Therefore, we propose the use of a classical web service to wrap quantum algorithms and expose them as endpoints.

In the same way, in [29], the researchers propose a procedure for the deployment of algorithms in cloud-based quantum computers. This procedure is only valid for circuit-based quantum algorithms because their proposal is based on starting from a generic quantum circuit and then compiling that circuit in a specific quantum computer.

The fact that quantum algorithms are highly dependent on the hardware on which they will be executed generates vendor lock-in problems. Therefore, there are already works that aim to minimize these problems by parameterizing quantum circuits [25, 30]. This technique allows the development of quantum circuits that can be modified by means of input parameters, thus being able to be used to adapt the algorithms to different computers or depending on the problem to be covered. However, this technique cannot be applied to quantum annealing-based hardware.

From a commercial technological perspective, along with Amazon Braket, there are different technological proposals related to the homogenization and simplification of quantum access to computers and services. A clear example is Azure Quantum [31], one of the main alternatives to Amazon Braket. Azure Quantum offers a quantum software development kit that attempts to unify a heterogeneous set of hardware and software solutions.

Other technology companies, software developers, and researchers are creating high-level development environments, toolkits, APIs, and other technologies to increase the level of abstraction of quantum software. For example, the IBM Company proposes the IBM Quantum environment [32], while other developers are focusing on specific areas such as quantum machine learning [20]. However, to the authors' knowledge, they do not provide any specific advantage over Amazon Braket for the development of quantum microservices or hybrid solutions.

Additionally, for the development of quantum microservices with a similar quality as that of classical services, it is not enough to simplify the development and deployment of quantum algorithms. For this, other aspects of service engineering [33] need to be taken into account.

Some researchers are focusing on the orchestration aspects of quantum complex algorithms. In [34] the authors propose a hardware-based orchestrator to control the flow of complex quantum and hybrid applications. However, for quantum microservices to be used with the same ease than classical services, software orchestration solutions are still needed.

In this sense, once microservices are deployed and orchestrated, they need to be managed. To this end, work lines around quantum DevOps practices are starting to emerge. In [35], the author proposes a methodology to test the reliability of quantum computers on a periodic manner. This reliability is used to estimate whether a given hardware will provide results of sufficient quality and to select the most suitable hardware available to run a quantum service.

Finally, in [36], the authors focus on trust and security issues in quantum services. The current model in which quantum services are managed introduces some trust issues regarding the specific hardware in which a given quantum task is run and other related issues.

All the papers presented in this section reveal that further research is needed to develop an effective quantum services engineering discipline.

8.6 Conclusion

In this chapter, we have presented an analysis of current quantum software from a service-oriented computing point of view. We have used Amazon Braket to deploy quantum services by wrapping them in a classical service and used prime factoring and traveling salesman problems as examples to hint the differences and intricacies of running the same service on a different quantum hardware, even when done under a common development umbrella and platform such as Braket.

This research and the derived work have allowed us to clearly present the current limitations in the construction and use of quantum services. To this end, we have organized these limitations and argued the intensive research efforts needed to bring the benefits of service-oriented computing to the quantum world.

Due to the young nature of quantum software engineering, most areas of this discipline, including service-oriented computing, are still in their first steps. However, the paradigm shift underlying quantum computing implies that there can be no direct translation of proposals and techniques. Running quantum algorithms as traditional services is not enough to fully explode their advantages; on the contrary, it will only degrade the solution.

Therefore, we believe that an effort is needed to generate new techniques, methodologies, and tools to fully expose all the perks and benefits, already demonstrated by cloud and service computing, into quantum software and services.

Acknowledgments This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), by the FPU19/03965 grant, by the Department of Economy and Infrastructure of the Government of Extremadura (GR18112, IB18030), and by the European Regional Development Fund.

References

1. Steane A (1998) Quantum computing. Rep Prog Phys 61(2):117
2. Preskill J (2018) Quantum computing in the nisq era and beyond. Quantum 2:79
3. MacQuarrie ER, Simon C, Simmons S, Maine E (2020) The emerging commercial landscape of quantum computing. Nat Rev Phys 2(11):596–598
4. McCaskey A, Dumitrescu E, Liakh D, Humble T (2018) Hybrid programming for near-term quantum computing systems. In: 2018 IEEE International Conference on Rebooting Computing (ICRC). IEEE, pp 1–12
5. Sodhi B (2018) Quality attributes on quantum computing platforms. arXiv preprint. arXiv:1803.07407
6. Dragoni N, Giallorenzo S, Lafuente AL, Mazzara M, Montesi F, Mustafin R, Safina L (eds) (2017) Microservices: yesterday, today, and tomorrow. Present Ulterior Softw Eng:195–216
7. Nielsen MA, Chuang I (2002) Quantum computation and quantum information
8. Newman S (2015) Building microservices: designing fine-grained systems. O'Reilly Media
9. Richardson C (2018) Microservices patterns: with examples in Java. Manning Publications
10. Martin Fowler and James Lewis. Microservices, a definition of this new architectural term. 2014.

11. Brown K, Woolf B (2016) Implementation patterns of microservices architectures. HILLSIDE Proc Conf Pattern Lang Prog 22:1–35
12. Schwichtenberg S, Gerth C, Engels G (2017) From open API to semantic specifications and code adapters. In: Proceedings – 2017 IEEE 24th International Conference on Web Services, ICWS 2017. Institute of Electrical and Electronics Engineers, pp 484–491
13. Balalaie A, Heydarnoori A, Jamshidi P (2016) Microservices architecture enables DevOps: migration to a cloud-native architecture. IEEE Software 33(3):42–52
14. Fitzgerald B, Stol KJ (2017) Continuous software engineering: a roadmap and agenda. J Syst Softw 123:176–189
15. Jiang S, Britt KA, McCaskey AJ, Humble TS, Kais S (2018) Quantum annealing for prime factorization. Scientific Rep 8(1):1–9
16. Haring R, Ohmacht M, Fox T, Gschwind M, Satterfield D, Sugavanam K, Coteus P, Heidelberger P, Blumrich M, Wisniewski R et al (2011) The ibm blue gene/q compute chip. IEEE Micro 32(2):48–60
17. Wang B, Feng H, Yao H, Wang C (2020) Prime factorization algorithm based on parameter optimization of Ising model. Scientific Rep 10(1):1–10
18. Motta M, Sun C, Tan ATK, O'Rourke MJ, Ye E, Minnich AJ, Brandao FGSL, Chan GK-L (2020) Determining eigenstates and thermal states on a quantum computer using quantum imaginary time evolution. Nat Phys 16(2):205–210
19. Kielpinski D, Monroe C, Wineland DJ (2002) Architecture for a large-scale ion-trap quantum computer. Nature 417(6890):709–711
20. Feng H, Wang B-N, Wang N, Wang C (2019) Quantum machine learning with d-wave quantum computer. Quantum Eng 1(2):e12
21. Warren RH (2013) Adapting the traveling salesman problem to an adiabatic quantum computer. Quantum Inf Proc 12(4):1781–1785
22. Irie H, Wongpaisarnsin G, Terabe M, Miki A, Taguchi S (2019) Quantum annealing of vehicle routing problem with time, state and capacity. In: International Workshop on Quantum Technology and Optimization Problems. Springer, pp 145–156
23. Papalitsas C, Andronikos T, Giannakis K, Theocharopoulou G, Fanarioti S (2019) A qubo model for the traveling salesman problem with time windows. Algorithms 12(11):224
24. Warren RH (2020) Solving the traveling salesman problem on a quantum annealer. SN Appl Sci 2(1):1–5
25. Matsuo A, Suzuki Y, Yamashita S (2020) Problem-specific parameterized quantum circuits of the VQE algorithm for optimization problems. arXiv
26. Srinivasan K, Satyajit S, Behera BK, Panigrahi PK (2018) Efficient quantum algorithm for solving travelling salesman problem: an IBM quantum experience. arXiv
27. Leymann F, Barzen J, Falkenthal M, Vietz D, Weder B, Wild K (2020) Quantum in the cloud: application potentials and research opportunities. In: Proceedings of the 10th International Conference on Cloud Computing and Service Science (CLOSER 2020). SciTePress, pp 9–24
28. Wild K, Breitenbücher U, Harzenetter L, Leymann F, Vietz D, Zimmermann M (2020) TOSCA4QC: two modeling styles for TOSCA to automate the deployment and orchestration of quantum applications. In: 24th IEEE International Enterprise Distributed Object Computing Conference, EDOC 2020, Eindhoven, The Netherlands, October 5–8, 2020. IEEE, pp 125–134
29. Sim S, Cao Y, Romero J, Johnson PD, Aspuru-Guzik A (2018) A framework for algorithm deployment on cloud-based quantum computers. arXiv preprint. arXiv:1810.10576
30. Adelomou AP, Ribe EG, Cardona XV (2020) Using the Parameterized Quantum Circuit combined with Variational-Quantum-Eigensolver (VQE) to create an Intelligent social workers' schedule problem solver. arXiv
31. Cuomo D, Caleffi M, Cacciapuoti AS (2020) Towards a distributed quantum computing ecosystem. IET Quantum Commun 1(1):3–8
32. Cross A (2018) The ibm q experience and qiskit open-source quantum computing software. APS March Meeting Abstracts 2018:L58–003

33. Li S, He Z, Jia Z, Zhong C, Cheng Z, Shan Z, Shen J, Babar MA (2021) Understanding and addressing quality attributes of microservices architecture: a systematic literature review. Inf Softw Technol 131:106449
34. Cohen Y, Sivan I, Ofek N, Ella L, Drucker N, Shani T, Weber O, Grinberg H, Greenbaum M (2020) Quantum orchestration platform integrated hardware and software for design and execution of complex quantum control protocols. Bull Am Phys Soc 65
35. Gheorghe-Pop I-D, Tcholtchev N, Ritter T, Hauswirth M (2020) Quantum devops: towards reliable and applicable nisq quantum computing. In: 2020 IEEE Globecom Workshops (GC Wkshps). IEEE, pp 1–6
36. Phalak K, Ash-Saki A, Alam M, Topaloglu RO, Ghosh S (2021) Quantum puf for security and trust in quantum computing. arXiv preprint. arXiv:2104.06244

Appendix S

Improving the assessment of older adults using feature selection and machine learning models

Authors: *Javier Rojo, Jose García-Alonso, Juan M. Murillo, Sumi Helal.*

Publication type: *Conference paper.*

Conference: *International Conference on Gerontechnology (ISG 2022).*

Year of publication: *2022.*

DOI: *10.4017/gt.2022.21.s.544.opp4*

Improving the assessment of older adults using feature selection and machine learning models

J. Rojo, J. García-Alonso, Juan M. Murillo, S. Helal

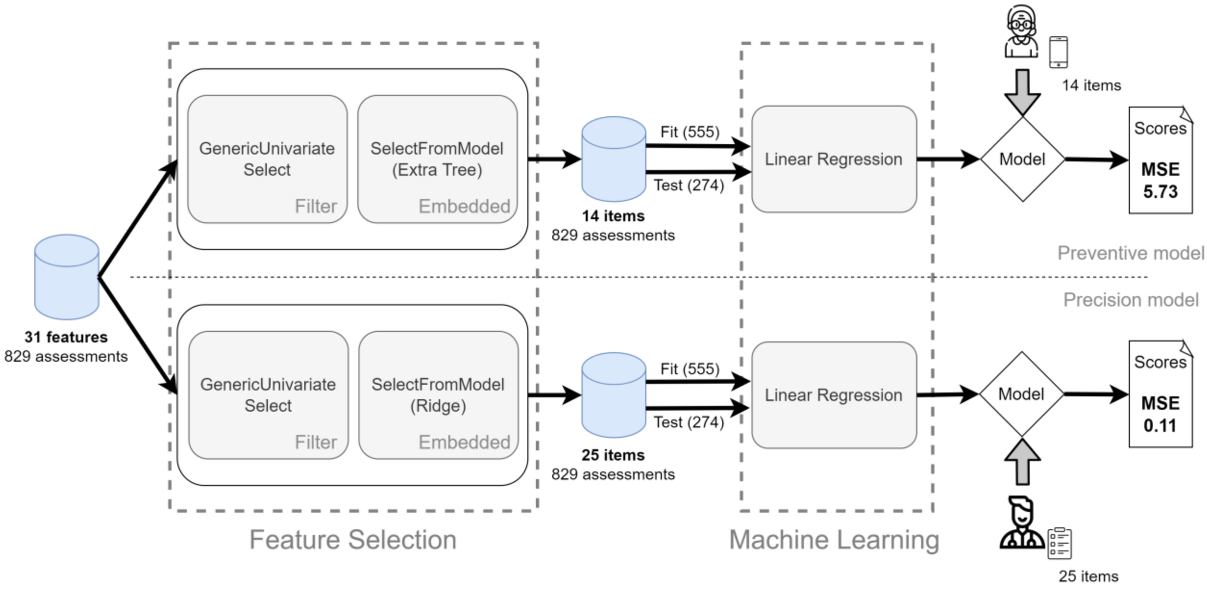
Purpose The growing capacity of healthcare systems to digitize patient information is enabling the creation of large repositories of patient health data, facilitating the use of Artificial Intelligence techniques, especifically Machine Learning, to analyze this data for insights and discovery. Thanks to this, unprecedented predictions and accurate diagnosis of certain diseases are possible to achieve today. However, this increasing morass of information is a double-edged sword as it makes it difficult for health professionals to navigate and determine which information is most crucial to examine for a given pathology or health condition. Feature Selection techniques have been applied for years to help Machine Learning prediction models to determine which information is most relevant to diagnoses, as demonstrated in Remeseiro et al. (2019). Consequently, these techniques help reduce the amount of information that health professionals need to collect, reducing laborious work while making them aware of which factors are more important for the assessment in contrast with what they initially considered to be important or relevant. **Method** We applied Feature Selection in the area of elder care. Specifically, we have studied the prediction of functional profiles of ageing adults currently performed routinely by 50 social and healthcare centers in Portugal using the Elderly Core Nursing Set (ENCS) form[1]. We used a web platform which calculates the state of the functional profile of the ageing adult as five continuous values between 0 and 100. We have taken the 31 items that are inputted to the form and analyzed them using different Feature Selection techniques. We used the selected features for the diagnosis of ageing adults in two phases (Figure 1). The first phase is carried out by the ageing adults themselves on their smartphones. The second phase was carried out by the caregivers. **Results and Discussion** first phase used only 14 (out of the 31) items and provided scores with a Mean Absolute Error (MAE) of 1.39 units (error percentage ranges from 1.54% to 3.08%) with respect to the original form. This error indicates the mean difference between the value of each score calculated using the original ENCS form and the one using our proposal. The caregivers phase used only 25 items which provided scores with an MAE of 0.17 units (error percentage ranges from 0.18% to 0.37%). Due to the range of values of the scores, the error introduced in the first phase precludes the use of its results as final assessments. However, it helps determine which users must be evaluated further using the depth with the second phase. The time required by a caregiver to assess the functional profile of an older adult has been reduced from an average of 20 minutes to 15 minutes and the number of unnecessary evaluations to healthy ageing adults has been decreased.

References

Remeseiro, B., & Bolon-Canedo, V. (2019). A review of feature selection methods in medical applications. Computers in biology and medicine, 112, 103375.

Keywords: Feature Selection, Machine Learning, Aging Informatics, Healthcare Data Analytics, eHealth
Address: School of Engineering, University of Extremadura, Spain
Email: javirojo@unex.es

Acknowledgement This work was supported by the projects 0499_4IE_PLUS_4_E (Interreg V-A España-Portugal 2014-2020) and RTI2018-094591-B-I00 (MCIU/AEI/FEDER, UE), the FPU19/03965 grant, the Department of Economy, Science and Digital Agenda of the Government of Extremadura (IB18030,GR21133), and the European Regional Development Fund.



[1] https://bio-protocol.org/bio101/r10088621

Figure 1. Proposal of solution

Acronyms

Ph.D. Philosophie Doctor.

PHT Personal Health Trajectory.

Bibliography

[1] Javier Rojo, Juan Hernandez, and Juan M Murillo. A personal health trajectory api: addressing problems in health institution-oriented systems. In *International Conference on Web Engineering*, pages 519–524. Springer, 2020.

[2] Alan R Hevner. A Three Cycle View of Design Science Research. Technical Report 2, 2007.

[3] Manuel Jesús-Azabal, Javier Rojo, Enrique Moguel, Daniel Flores-Martin, Javier Berrocal, José García-Alonso, and Juan M Murillo. Voice assistant to remind pharmacologic treatment in elders. In *International Workshop on Gerontechnology*, pages 123–133. Springer, 2019.

[4] Javier Rojo, Daniel Flores-Martin, Jose Garcia-Alonso, Juan M Murillo, and Javier Berrocal. Automating the interactions among iot devices using neural networks. In *2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, pages 1–6. IEEE, 2020.

[5] Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan M Murillo. Smart nursing homes: Self-management architecture based on iot and machine learning for rural areas. *Wireless Communications and Mobile Computing*, 2021, 2021.

[6] Javier Rojo, Jose Garcia-Alonso, Javier Berrocal, Juan Hernández, Juan Manuel Murillo, and Carlos Canal. Sowcompact: A federated process mining method for social workflows. *Information Sciences*, 595:18–37, 2022.

[7] Javier Rojo, José García-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, and Carlos Canal. Social events analyzer (sea): A toolkit for mining social workflows by means of federated process mining. In *International Conference on Web Engineering*, pages 477–480. Springer, 2022.

[8] Javier Rojo, Juan Hernández, Juan M Murillo, and Jose Garcia-Alonso. Blockchains' federation for integrating distributed health data using a patient-centered approach. In *2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH)*, pages 52–59. IEEE, 2021.

[9] Javier Rojo, Juan Hernández, Sumi Helal, Juan M Murillo, and José García-Alonso. Blockchain-supported health registry: The claim for a personal health trajectory traceability and how it can be achieved. In *International Workshop on Gerontechnology*, pages 22–33. Springer, 2022.

[10] Javier Rojo, Enrique Moguel, Cesar Fonseca, Manuel Lopes, Jose Garcia-Alonso, and Juan Hernandez. Time series forecasting to predict the evolution of the functional profile of the elderly persons. In *International Workshop on Gerontechnology*, pages 11–22. Springer, 2020.

[11] Javier Rojo, Lara Guedes de Pinho, César Fonseca, Manuel José Lopes, Sumi Helal, Juan Hernández, Jose Garcia-Alonso, and Juan Manuel Murillo. Analyzing the performance of feature selection on regression problems: A case study on older adults' functional profile. *IEEE Transactions on Emerging Topics in Computing*, 2022.

[12] David Valencia, Jose Garcia-Alonso, Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan Manuel Murillo. Hybrid classical-quantum software services systems: Exploration of the rough edges. In *International Conference on the Quality of Information and Communications Technology*, pages 225–238. Springer, 2021.

[13] Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, and Juan Manuel Murillo. Quantum software as a service through a quantum api gateway. *IEEE Internet Computing*, 26(1):34–41, 2021.

[14] Arthur Gatouillat, Youakim Badr, Bertrand Massot, and Ervin Sejdic. Internet of Medical Things: A Review of Recent Contributions Dealing with Cyber-Physical Systems in Medicine. *IEEE Internet of Things Journal*, 5(5):3810–3822, oct 2018.

[15] Alex Roehrs, Cristiano André da Costa, Rodrigo da Rosa Righi, Valter Ferreira da Silva, José Roberto Goldim, and Douglas C. Schmidt. Analyzing the performance of a blockchain-based personal health record implementation. *Journal of Biomedical Informatics*, 92:103140, 2019.

[16] Susan J. Henly, Jean F. Wyman, and Joseph E. Gaugler. Health trajectory research: A call to action for nursing science. *Nursing Research*, 60(3 SUPPL.), may 2011.

[17] Hyun Jung La. A conceptual framework for trajectory-based medical analytics with IoT contexts. *Journal of Computer and System Sciences*, 82(4):610–626, jun 2016.

[18] Khader Shameer, Marcus A. Badgeley, Riccardo Miotto, Benjamin S. Glicksberg, Joseph W. Morgan, and Joel T. Dudley. Translational bioinformatics in the era of real-time biomedical, health care and wellness data streams. *Briefings in Bioinformatics*, 18(1):105–124, 2017.

[19] Plume's Latest Market Report Reveals Major Shifts in Smart Home Usage.

[20] IoT connected devices worldwide 2019-2030 — Statista.

[21] IoT devices installed base worldwide 2015-2025 — Statista.

[22] IoT connected devices by use case 2030 — Statista.

[23] Rebecca Mathews, Chris O'Malley, Jenny M Hall, Leah Macaden, Sandra MacRury, et al. Diabetes, care homes, and the influence of technology on practice and care delivery in care homes: systematic review and qualitative synthesis. *JMIR diabetes*, 4(2):e11526, 2019.

[24] Darla J Hamann and Karabi C Bezboruah. Outcomes of health information technology utilization in nursing homes: Do implementation processes matter? *Health Informatics Journal*, 26(3):2249–2264, 2020.

[25] • Global IoT in healthcare market size 2019 — Statista.

[26] Fadi Al-Turjman, Muhammad Hassan Nawaz, and Umit Deniz Ulusar. Intelligence in the internet of medical things era: A systematic review of current and future trends. *Computer Communications*, 150:644–660, 2020.

[27] Timo Sztyler, Johanna Völker, Josep Carmona, Oliver Meier, and Heiner Stuckenschmidt. Discovery of personal processes from labeled sensor data - An application of process mining to personalized health care. In *CEUR Workshop Proceedings*, volume 1371, pages 31–46. CEUR-WS, 2015.

[28] Nelson Pacheco Rocha, Ana Dias, Gonçalo Santinha, Mário Rodrigues, Alexandra Queirós, and Carlos Rodrigues. Smart cities and healthcare: A systematic review. *Technologies*, 7(3):58, 2019.

[29] Taher M Ghazal, Mohammad Kamrul Hasan, Muhammad Turki Alshurideh, Haitham M Alzoubi, Munir Ahmad, Syed Shehryar Akbar, Barween Al Kurdi, and Iman A Akour. Iot for smart cities: Machine learning approaches in smart healthcare—a review. *Future Internet*, 13(8):218, 2021.

[30] 10 internet of things (IoT) healthcare examples.

[31] Zarlish Ashfaq, Abdur Rafay, Rafia Mumtaz, Syed Mohammad Hassan Zaidi, Hadia Saleem, Syed Ali Raza Zaidi, Sadaf Mumtaz, and Ayesha Haque. A review of enabling technologies for internet of medical things (iomt) ecosystem. *Ain Shams Engineering Journal*, 13(4):101660, 2022.

[32] Daniel Flores-Martin, Javier Berrocal, José García-Alonso, and Juan M Murillo. Towards dynamic and heterogeneous social iot environments. *Computing*, pages 1–24, 2022.

[33] NA Abu Bakar, Wan Makhtariah Wan Ramli, and Noor Hafizah Hassan. The internet of things in healthcare: an overview, challenges and model plan for security risks management process. *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, 15(1):414–420, 2019.

[34] Iuliana Chiuchisan, Hariton-Nicolae Costin, and Oana Geman. Adopting the internet of things technologies in health care systems. In *2014 International Conference and Exposition on Electrical and Power Engineering (EPE)*, pages 532–535. IEEE, 2014.

[35] Mohamad Kassab, Joanna Defranco, Tarek Malas, Valdemar Vicente Graciano Neto, and Giuseppe Destefanis. Blockchain: A panacea for electronic health records? In *Proceedings - 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare, SEH 2019*, pages 21–24. Institute of Electrical and Electronics Engineers Inc., may 2019.

[36] Alex Roehrs, Cristiano André Da Costa, Rodrigo Da, Rosa Righi, Kleinner, and Silva Farias De Oliveira. Personal Health Records: A Systematic Literature Review. *Journal of Medical Internet Research*, 19(1):e13, 2017.

[37] A. Dubovitskaya, P. Novotny, S. Thiebes, A. Sunyaev, M. Schumacher, Z. Xu, and F. Wang. Intelligent health care data management using blockchain: current limitation and future research agenda. In *Heterogeneous Data Management, Polystores, and Analytics for Healthcare*, pages 277–288. 2019.

[38] Ton Spil and Rich Klein. Personal health records success; why google health failed and what does that mean for Microsoft HealthVault? In *Proceedings of the Annual Hawaii International Conference on System Sciences*, pages 2818–2827. IEEE Computer Society, 2014.

[39] Michael Kyazze, Janet Wesson, and Kevin Naude. The design and implementation of a ubiquitous personal health record system for south africa. *Studies in health technology and informatics*, 206:29, 2014.

[40] Alex Roehrs, Cristiano André da Costa, and Rodrigo da Rosa Righi. OmniPHR: A distributed architecture model to integrate personal health records. *Journal of Biomedical Informatics*, 71:70–81, jul 2017.

[41] Simon Lebech Cichosz, Mads Nibe Stausholm, Thomas Kronborg, Peter Vestergaard, and Ole Hejlesen. How to Use Blockchain for Diabetes Health Care Data and Access Management: An Operational Concept. *Journal of Diabetes Science and Technology*, 13(2):248–253, mar 2019.

[42] Sudeep Tanwar, Karan Parekh, and Richard Evans. Blockchain-based electronic healthcare record system for healthcare 4.0 applications. *Journal of Information Security and Applications*, 50:102407, feb 2020.

[43] Guang Yang, Chunlei Li, and Kjell E. Marstein. A blockchain-based architecture for securing electronic health record systems. *Concurrency and Computation: Practice and Experience*, 33(14):e5479, jul 2021.

[44] Yin Zhang, Meikang Qiu, Chun-Wei Tsai, Mohammad Hassan, and Atif Alamri. Health-cps: Healthcare cyber-physical system assisted by cloud and big data. *IEEE Systems Journal*, 11:1–8, 08 2015.

[45] Xiao Wang, Aiqing Zhang, Xiaojuan Xie, and Xinrong Ye. Secure-aware and privacy-preserving electronic health record searching in cloud environment. *International Journal of Communication Systems*, 32(8):e3925, may 2019.

[46] S. Bhavya and Anitha S. Pillai. Prediction models in healthcare using deep learning. In *Advances in Intelligent Systems and Computing*, volume 1182 AISC, pages 195–204. Springer, dec 2021.

[47] Chonho Lee, Zhaojing Luo, Kee Yuan Ngiam, Meihui Zhang, Kaiping Zheng, Gang Chen, Beng Chin Ooi, and Wei Luen James Yip. Big Healthcare Data Analytics: Challenges and Applications. pages 11–41. Springer, Cham, 2017.

[48] Sarah Itani, Fabian Lecron, and Philippe Fortemps. Specifics of medical data mining for diagnosis aid: A survey, mar 2019.

[49] Hafiz TA Khan. Population ageing in a globalized world: Risks and dilemmas? *Journal of evaluation in clinical practice*, 25(5):754–760, 2019.

[50] Yingzi Wang, Xiao Zhou, Anastasios Noulas, Cecilia Mascolo, Xing Xie, and Enhong Chen. Predicting the spatio-temporal evolution of chronic diseases in population with human mobility data. In *IJCAI International Joint Conference on Artificial Intelligence*, volume 2018-July, pages 3578–3584. International Joint Conferences on Artificial Intelligence, 2018.

[51] Charles Flicker, Steven H. Ferris, and Barry Reisberg. Mild cognitive impairment in the elderly. *Neurology*, 41(7):1006–1006, 1991.

[52] Jeremy M. Jacobs, Yoram Maaravi, Aaron Cohen, Michael Bursztyn, Eliana Ein-Mor, and Jochanan Stessman. Changing Profile of Health and Function from Age 70 to 85 Years. *Gerontology*, 58(4):313–321, jun 2012.

[53] Cheng Sheng Yu, Yu Jiun Lin, Chang Hsien Lin, Shiyng Yu Lin, Jenny L. Wu, and Shy Shin Chang. Development of an online health care assessment for preventive medicine: A machine learning approach. *Journal of Medical Internet Research*, 22(6), jun 2020.

[54] Susan Sabra, Khalid Mahmood Malik, Muhammad Afzal, Vian Sabeeh, and Ahmad Charaf Eddine. A hybrid knowledge and ensemble classification approach for prediction of venous thromboembolism. In *Expert Systems*, volume 37. Blackwell Publishing Ltd, feb 2020.

[55] Natalia Norori, Qiyang Hu, Florence Marcelle Aellen, Francesca Dalia Faraci, and Athina Tzovara. Addressing bias in big data and ai for health care: A call for open science. *Patterns*, 2(10):100347, 2021.

[56] João R Gonçalves, Isabel Ramalhinho, Betsy L Sleath, Manuel J Lopes, and Afonso M Cavaco. Probing pharmacists' interventions in long-term care: a systematic review. *European geriatric medicine*, pages 1–21, 2021.

[57] Samuel H. Huang, Lawson R. Wulsin, Hua Li, and Jeff Guo. Dimensionality reduction for knowledge discovery in medical claims database: Application to antidepressant medication utilization study. *Computer Methods and Programs in Biomedicine*, 93(2):115–123, feb 2009.

[58] Chaim M Bell, Sally S Araki, and Peter J Neumann. The association between caregiver burden and caregiver health-related quality of life in

alzheimer disease. *Alzheimer Disease & Associated Disorders*, 15(3):129–136, 2001.

[59] Carla Silveira, Renato T Souza, Maria L Costa, Mary A Parpinelli, Rodolfo C Pacagnella, Elton C Ferreira, Jussara Mayrink, José P Guida, Maria H Sousa, Lale Say, et al. Validation of the who disability assessment schedule (whodas 2.0) 12-item tool against the 36-item version for measuring functioning and disability associated with pregnancy and history of severe maternal morbidity. *International Journal of Gynecology & Obstetrics*, 141:39–47, 2018.

[60] Shin Ho Park, Eleni A Demetriou, Karen L Pepper, Yun Ju C Song, Emma E Thomas, Ian B Hickie, Nick Glozier, and Adam J Guastella. Validation of the 36-item and 12-item self-report world health organization disability assessment schedule ii (whodas-ii) in individuals with autism spectrum disorder. *Autism Research*, 12(7):1101–1111, 2019.

[61] Girish Chandrashekar and Ferat Sahin. A survey on feature selection methods. *Computers and Electrical Engineering*, 40(1):16–28, jan 2014.

[62] A. Suresh, R. Kumar, and R. Varatharajan. Health care data analysis using evolutionary algorithm. *Journal of Supercomputing*, 76(6):4262–4271, jun 2020.

[63] Bodur and Atsa'am. Filter Variable Selection Algorithm Using Risk Ratios for Dimensionality Reduction of Healthcare Data for Classification. *Processes*, 7(4):222, apr 2019.

[64] Jennifer G Dy and Carla E Brodley. Feature selection for unsupervised learning. *Journal of machine learning research*, 5(Aug):845–889, 2004.

[65] Davide Chicco and Luca Oneto. Data analytics and clinical feature ranking of medical records of patients with sepsis. *BioData Mining*, 14(1), dec 2021.

[66] Mohammad Masoud Javidi. Feature selection schema based on game theory and biology migration algorithm for regression problems. *International Journal of Machine Learning and Cybernetics*, 12(2):303–342, feb 2021.

[67] Rong Fang Xu and Shie Jue Lee. Dimensionality reduction by feature clustering for regression problems. *Information Sciences*, 299:42–57, apr 2015.

[68] Tawseef Ayoub Shaikh and Rashid Ali. Quantum computing in big data analytics: A survey. In *2016 IEEE international conference on computer and information technology (CIT)*, pages 112–115. IEEE, 2016.

[69] Raihan Ur Rasool, Hafiz Farooq Ahmad, Wajid Rafique, Adnan Qayyum, and Junaid Qadir. Quantum computing for healthcare: A review. 2022.

[70] Shivam Gupta, Sachin Modgil, Priyanka C Bhatt, Charbel Jose Chiappetta Jabbour, and Sachin Kamble. Quantum computing led innovation for achieving a more sustainable covid-19 healthcare industry. *Technovation*, page 102544, 2022.

[71] Joseph Davids, Niklas Lidströmer, and Hutan Ashrafian. Artificial intelligence in medicine using quantum computing in the future of healthcare. In *Artificial Intelligence in Medicine*, pages 423–446. Springer, 2022.

[72] Maksut Senbekov, Timur Saliev, Zhanar Bukeyeva, Aigul Almabayeva, Marina Zhanaliyeva, Nazym Aitenova, Yerzhan Toishibekov, and Ildar Fakhradiyev. The recent progress and applications of digital technologies in healthcare: a review. *International journal of telemedicine and applications*, 2020, 2020.

[73] Dipak Kalra. Electronic health record standards. 2006.

[74] A. Stiell, A.J. Forster, I.G. Stiell, and C. Van Walraven. Prevalence of information gaps in the emergency department and the effect on patient outcomes. *CMAJ*, 169(10):1023–1028, 2003. cited By 151.

[75] Belén Prados-Suárez, Carlos Molina Fernández, and Carmen Peña Yañez. Electronic Health Records Aggregators (EHRagg). *Methods of Information in Medicine*, 59(02/03):096–103, may 2020.

[76] Kai Fan, Shangyang Wang, Yanhui Ren, Hui Li, and Yintang Yang. MedBlock: Efficient and Secure Medical Data Sharing Via Blockchain. *Journal of Medical Systems*, 42(8):1–11, aug 2018.

[77] Beatriz Remeseiro and Veronica Bolon-Canedo. A review of feature selection methods in medical applications, sep 2019.

[78] David José Murteira Mendes, Manuel José Lopes, José Manuel García-Alonso, Jorge Santos, and Luís Manuel Mota Sousa. Resilient software architecture platform for the individual care plan. In *Exploring the Role of ICTs in Healthy Aging*, pages 13–32. IGI Global, 2020.

[79] Manuel Lopes, Lara Pinho, César Fonseca, Margarida Goes, Henrique Oliveira, and José Garcia-Alonso. Functioning in institutionalized and noninstitutionalized older adults: A comparative study. 2020.

[80] Margarida Goes, Manuel José Lopes, João Marôco, Henrique Oliveira, César Fonseca, Lisete Mónico, Pedro Parreira, José García-Alonso, and Lara Guedes de Pinho. The quality of life of older individuals following the world health organization assessment criteria. *Geriatrics*, 5(4):102, 2020.

[81] JM Garcia-Alonso, Javier Berrocal, Borja Rivero Jiménez, DC Caballero, LM Juárez, JM Rodríguez, David Mendes, Cesar Fonseca, MJ Lopes, and AP Vereda. Instituto internacional de investigacion e innovacion del envejecimiento. 2018.

[82] Sheila Bonilla Plaza. Technological developments for an ageing and rural society. Technical report, Máster Universitario en Ingeniería Informática. Universidad de Extremadura, aug 2019.

[83] Enrique Moguel, Javier Berrocal, Juan M. Murillo, José García-Alonso, David Mendes, Cesar Fonseca, and Manuel Lopes. Enriched elderly virtual profiles by means of a multidimensional integrated assessment platform. In *Procedia Computer Science*, volume 138, pages 56–63. Elsevier B.V., jan 2018.

[84] Daniel Flores-Martin, Javier Berrocal, José García-Alonso, Carlos Canal, and Juan M Murillo. Enabling the interconnection of smart devices through semantic web techniques. In *International Conference on Web Engineering*, pages 534–537. Springer, 2019.

[85] Paul Johannesson and Erik Perjons. *An Introduction to Design Science*. Springer International Publishing, Cham, 2014.

[86] Alan R Hevner, Salvatore T March, Jinsoo Park, and Sudha Ram. DESIGN SCIENCE IN INFORMATION SYSTEMS RESEARCH 1. Technical Report 1, 2004.

[87] Daniel Flores-Martin, Javier Rojo, Enrique Moguel, Javier Berrocal, and Juan M Murillo. Smart nursing homes: Self-management architecture based on iot and machine learning for rural areas (summary). 2021.

[88] Javier Rojo, José Garcıa-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, and Carlos Canal. Sowcompact: A federated process mining method for social workflows (summary). 2022.

[89] Javier Rojo, José Garcıa-Alonso, Javier Berrocal, Juan Hernández, Juan M Murillo, and Carlos Canal. Social events analyzer (sea): Un toolkit para minar social workflows mediante federated process mining. 2021.

[90] Ngoako Solomon Marutha. Cooperative collaboration amongst healthcare institutions towards central access to medical with patients records: Striving for quality care worldwide. In *Cooperation and Collaboration Initiatives for Libraries and Related Institutions*, pages 62–79. IGI Global, 2020.

[91] Javier Rojo, Juan Hernandez, Luca Foschini, Paolo Bellavista, Javier Berrocal, Juan M Murillo Rodriguez, and José García-Alonso. Blockchains' federation for enabling actor-centered data integration. In *ICC 2022-IEEE International Conference on Communications*, pages 3430–3435. IEEE, 2022.

[92] Javier Rojo, Jose Garcia-Alonso, Juan M Murillo, and Sumi Helal. Improving the assessment of older adults using feature selection and machine learning models. 21:544–544, 2022.

[93] Jaime Alvarado-Valiente, Javier Romero-Alvarez, Javier Rojo, Enrique Moguel, Jose Garcıa-Alonso, and Juan M Murillo. Sowcompact: A federated process mining method for social workflows (summary). 2022.

[94] Javier Rojo, David Valencia, Javier Berrocal, Enrique Moguel, Jose Garcia-Alonso, and Juan Manuel Murillo Rodriguez. Trials and tribulations of developing hybrid quantum-classical microservices systems. *2nd Quantum Software Engineering and Technology Workshop*, 3008:1–16, 2021.

[95] Jose Garcia-Alonso, Javier Rojo, David Valencia, Enrique Moguel, Javier Berrocal, and Juan Manuel Murillo. Quantum software as a service through a quantum api gateway (summary). 2022.

[96] Javier Romero-Alvarez, Jaime Alvarado-Valiente, Javier Rojo, Enrique Moguel, Jose Garcıa-Alonso, and Juan M Murillo. Sowcompact: A federated process mining method for social workflows (summary). 2022.

[97] David Valencia, Enrique Moguel, Javier Rojo, Javier Berrocal, Jose Garcia-Alonso, and Juan M. Murillo. *Quantum Service-Oriented Architectures: From Hybrid Classical Approaches to Future Stand-Alone Solutions*, pages 149–166. Springer International Publishing, Cham, 2022.

[98] Enrique Moguel, Javier Rojo, David Valencia, Javier Berrocal, Jose Garcia-Alonso, and Juan M Murillo. Quantum service-oriented computing: current landscape and challenges. *Software Quality Journal*, pages 1–20, 2022.

[99] Nasreen Khan, Robert Kaestner, and Swu-Jane Lin. Effect of prescription drug coverage on health of the elderly. *Health services research*, 43(5p1):1576–1597, 2008.

[100] Matthew B Hoy. Alexa, siri, cortana, and more: an introduction to voice assistants. *Medical reference services quarterly*, 37(1):81–88, 2018.

[101] Pilar Rodríguez Rodríguez. Envejecimiento en el mundo rural: necesidades singulares, políticas específicas. *Perfiles y tendencias*, 11:30, 2004.

[102] Roberto Cardarelli, Christopher Mann, Kimberly G Fulda, Elizabeth Balyakina, Anna Espinoza, and Sue Lurie. Improving accuracy of medication identification in an older population using a medication bottle color symbol label system. *BMC family practice*, 12(1):1–8, 2011.

[103] Gabriel Machado Lunardi, Fadi Al Machot, Vladimir A. Shekhovtsov, Vinícius Maran, Guilherme Medeiros Machado, Alencar Machado, Heinrich C. Mayr, and José Palazzo M. de Oliveira. IoT-based human action prediction and support. *Internet of Things*, 3-4:52–68, oct 2018.

[104] Gabriela F Ciocarlie, Bogdan Copos, Ioannis Agadakos, Gabriela Ciocarlie, Tancrède Lepoint, Ulf Lindqvist, and Michael Locasto. Butterfly Effect: Causality from Chaos in the IoT. Technical report, 2018.

[105] Fabio Paternò and Sadi Alawadi. Towards Intelligent Personalization of IoT Platforms End User Development; Internet of Things; Trigger-Action Programming ACM Reference format. Technical report, 2019.

[106] Basman M.Hasan Alhafidh, Amar I. Daood, and William H. Allen. Poster abstract: Comparison of classifiers for prediction of human actions in a smart home. In *Proceedings - ACM/IEEE International Conference on Internet of Things Design and Implementation, IoTDI 2018*, pages 287–288. Institute of Electrical and Electronics Engineers Inc., may 2018.

[107] Basman M. Hasan Alhafidh, Amar I. Daood, and William H. Allen. Prediction of Human Actions in a Smart Home Using Single and Ensemble of Classifiers. In *SoutheastCon 2018*, pages 1–8. IEEE, apr 2018.

[108] C W Gunther, H M W Verbeek, Den Dolech, A Z Eindhoven, Christian W Günther, and Eric Verbeek. XES-standard definition. Technical report, 2014.

[109] E. Allen EMERSON. Chapter 16 - temporal and modal logic. In JAN VAN LEEUWEN, editor, *Formal Models and Semantics*, Handbook of Theoretical Computer Science, pages 995 – 1072. Elsevier, Amsterdam, 1990.

[110] Huanhuan Feng, Xiang Wang, Yanqing Duan, Jian Zhang, and Xiaoshuan Zhang. Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges. *Journal of Cleaner Production*, 260:121031, 2020.

[111] Juan F Galvez, Juan C Mejuto, and Jesus Simal-Gandara. Future challenges on the use of blockchain for food traceability analysis. *TrAC Trends in Analytical Chemistry*, 107:222–232, 2018.

[112] Giovanni Mirabelli and Vittorio Solina. Blockchain and agricultural supply chains traceability: Research trends and future challenges. *Procedia Manufacturing*, 42:414–421, 2020.

[113] Been Kim, Julie A Shah, and Finale Doshi-Velez. Mind the gap: A generative approach to interpretable feature selection and extraction. 2015.

[114] Karen Fuchs, Jan Gertheiss, and Gerhard Tutz. Nearest neighbor ensembles for functional data with interpretable feature selection. *Chemometrics and Intelligent Laboratory Systems*, 146:186–197, 2015.

[115] David Gunning, Mark Stefik, Jaesik Choi, Timothy Miller, Simone Stumpf, and Guang-Zhong Yang. Xai—explainable artificial intelligence. *Science Robotics*, 4(37), 2019.

[116] Simon Schwichtenberg, Christian Gerth, and Gregor Engels. From open api to semantic specifications and code adapters. In *2017 IEEE International Conference on Web Services (ICWS)*, pages 484–491. IEEE, 2017.

[117] Xiongfeng Ma, Xiao Yuan, Zhu Cao, Bing Qi, and Zhen Zhang. Quantum random number generation. *npj Quantum Information*, 2(1):1–9, 2016.

[118] Davide Taibi, Valentina Lenarduzzi, and Claus Pahl. Architectural patterns for microservices: A systematic mapping study. In *CLOSER*, pages 221–232, 2018.

[119] Leonardo Alchieri, Davide Badalotti, Pietro Bonardi, and Simone Bianco. An introduction to quantum machine learning: from quantum logic to quantum deep learning. *Quantum Machine Intelligence*, 3(2):1–30, 2021.

[120] José D Martín-Guerrero and Lucas Lamata. Quantum machine learning: A tutorial. *Neurocomputing*, 470:457–461, 2022.