Preventive maintenance optimisation of accessible flat roofs in healthcare centres using the Markov chain

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Abstract

Technical installations can be placed on accessible flat roofs in hospitals. However, flat roofs also increase the risk of leaks and other drawbacks, which may alter the ordinary conditions of use of the building. This research aims to optimise the periodicity of flat roofs maintenance operations in hospitals to increase their useful life and guarantee their reliability. This research considered flat accessible roofs with three types of waterproofing membranes: bitumen, PVC and elastomeric. A sample of 12 hospitals in Extremadura (Spain) was processed using the Markov Chain. The results show that the degradation of flat roofs can be estimated and consequently the most appropriate maintenance plan considering reliability. The authors found that preventive maintenance contributed towards extending the lifetime of the roofs up to 8 years with reliability exceeding 63.21%. In this respect, the PVC membrane was found to suffer the least degradation. The average operating life of the membranes was calculated: 28 years for PVC, 24 years for elastomer and 21 years for bitumen. The time between replacements was also estimated, which means maintenance operations can be systematised to optimise costs and boost reliability.

Keywords: Markov chain; maintenance policies; healthcare engineering; flat roof; reliability

Introduction

Flat roofs are a construction element that can be used for installations or another usage [1]. A flat inverted roof includes a layer of thermal insulation that protects the waterproofing layer [2], made of watertight membranes (bituminous, PVC or elastomeric), which protects the building from water seeping through [3]. The most common waterproofing membranes used in flat roofs are hydrocarbon (asphalt or bitumen), polymer (EPDM - ethylene propylene diene monomer) and PVC (polyvinyl chloride) [4]. There are different types of elastomeric membranes (cold, liquid, spreadable and self-adhesive), which differ in chemical composition and application [5]. Bituminous membranes are made from SBS (styrene-butadiene-styrene) or APP (atactic polypropylene) modified bitumen [6]. PVC membranes are reinforced with a fibreglass mesh and include various additives to improve their resistance to adverse weather conditions [7].

The roof is one of the building component that present the greatest number of problems [8], as the most common building pathologies are due to water infiltrations [9]. Dampness can appear due to problems in the different phases of the construction process, either in the design stage, execution or use of the building [10]. It is, therefore, necessary to systematise the maintenance processes [11]. Flat roofs allow hospitals to locate HVAC, solar thermal domestic hot water (DHW) and photovoltaic panel energy generation facilities on the outside of the building [12, 13] and carry out maintenance in a safe manner without disruption. Moreover, choosing a roof with proper solar reflectance decrease the average energy consumption [14]. However, hospitals are buildings that must be operational every day of the year, and its envelope must not be compromised by water leaks, which could lead to the undesirable growth of fungi and bacteria.

Carretero-Ayuso, García-Sanz-Calcedo and Reyes Rodríguez [15] analysed 44 building projects drawn up between 2000 and 2007 to detect the common errors that designers make when designing flat roofs. They found that the projects contained many errors that would inevitably lead to future pathologies, due to dampness of the roof and lack of watertightness. They also identified the most common errors with a higher risk of producing incidents, although they did not go into detail on maintenance aspects: the installation of the membrane does not provide the minimum required height from the roof floor, minimum construction detail are not included, the membrane of critical zones are not reinforced, materials no compatible with the membranes are used, among others.

Although 65% of the operating costs of a building during its life cycle correspond to maintenance and operating expenses [16], in a hospital, operating costs are higher, mainly due to the high intensity of use, as it operates 24 hours a day, 365 days a year [17]. Carretero-Ayuso and García Sanz-Calcedo [18] analysed the usual design faults in the building envelope of 17 healthcare centre projects with flat roofs in Extremadura (Spain). They detected 344 incidents, specified in 51 control parameters: specific data of drains and drainage nozzles are not provided; no construction details or data for the resolution of thermal bridges in the structure are provided; lack of semi-circular gutters, renders or primers in singularities; watertightness or air permeability is not specified; lack of prevention of moisture protection measures at the bottom of the facades, among others.

Flat roofs have advantages over other architectural solutions. For example, Marrana *et al.* [19] studied 472 flat roofs and found that the costs associated with their life cycle were more advantageous in economic and energy terms. In contrast, the costs of materials were the most decisive and inverted roofs with limited accessibility are cheaper. However, hospital roofs must be accessible to facilitate maintenance operations [20].

Gonçalves *et al.* [21] used life cycle analysis (LCA) to observe that bituminous membranes were the best option and that synthetic EPDM membranes were more expensive and had a higher environmental impact. Nevertheless, if the influence of the cost of the membranes reduces by 34% in the multi-criteria analysis, the best option would be TPO (Thermoplastic Polyolefin) membranes. The risk of failure in flat roofs is high, as numerous anomalies can affect their functionality, among others: penetration of moisture, the appearance of fungi, fracture, cracking, detachment or poor positioning of the layers, bulging, punctures or wrinkling that impairs the functionality of the roof, an inadequate slope that generates a possible pooling and poor design in the construction process [22].

Markov chains is a probabilistic tool that can be used to model the degradation suffered by a certain system, simulating its degradation process [23]. In this model, the future state of degradation only depends on the present state of deterioration and not on the past. Therefore, it is possible to predict the future condition of flat roofs, optimizing the maintenance operations required to keep the deterioration controlled and not affecting their performance. The Markov model has been used on several occasions to estimate the deterioration of the various critical components of a building [24, 25]. This stochastic model allows analysing the probability of failure of a part and the likelihood of reaching a state beyond its proper functionality [26]. Although the Markov Chain is considered an adequate tool for the optimisation of maintenance, its application in healthcare centres is very scarce.

Velázquez-Martínez, Cruz-Suárez, and Santos-Reyes [27] analysed the safety culture of a Mexican hospital using Markov chains and estimated the evolutionary behaviour over time. Cheng, Wang, and Yan [28] carried out an optimal design of the Cold Water for Human Consumption (CWHC) facilities by applying different statistical prediction techniques, using the Markov chains to obtain the probability distribution of the state of the facility and its reliability. Papakonstantinou and Shinozuka [29] used partially observable Markov decision processes to find appropriate maintenance, inspection and management policies to control corrosion in structures. They combined four maintenance options and three inspection actions, demonstrating that Markov model is suitable for solving multiple degradation models.

Gómez and Carnero [30] applied the Markov chains to determine the most appropriate maintenance policy for the medical gas distribution subsystems of a public hospital.

Silva *et al.* [31] used the Markov chains to obtain the degradation suffered by three types of façade cladding: stone, ceramic and paint, and determined how the characteristics of the coating influenced the degradation. They also analysed the impact of the distance to the sea or humidity on degradation. Ortega Madrigal *et al.* [32] proposed several methods to predict façade and the most common roof life cycles, among which were the Markov model. They compared different construction systems to facilitate the technician's work in the building design phase. Edirisinghe, Zhang, and Setunge [33] modelled the deterioration of various critical construction components of community buildings, using Markov chains, obtaining models to reliably predict their decline, determining the main factors of influence. Coffelt, Hendrickson, and Healey [34] applied the Markov model to assess the deterioration of commercial roof systems and maintenance according to the condition, water leaks and cost. Ferreira *et al.* [35] also modelled the degradation of ceramic façade coverings, by inspecting 195 buildings in Lisbon using a Petri dish network and the stochastic model proposed by the Markov chains.

As evidenced in state of the art, there are precedents for previous work using the Markov model to estimate the degradation of various critical components in the building. However, no references from authors have applied this probabilistic model to hospital roofs, to optimise their preventive maintenance, control their reliability and reduce their operating costs and the risks of failure. Therefore, applying this methodology to hospital buildings is novel.

This research aims to optimise the periodicity of maintenance operations of flat roofs in hospitals using Markov chains as a model for monitoring condition-based maintenance. Thus, maintenance operations could be protocoled, which would reduce their cost and increase the intrinsic reliability of the roof.

Method

The three types of accessible flat roofs shown in Figure 1 were analysed.

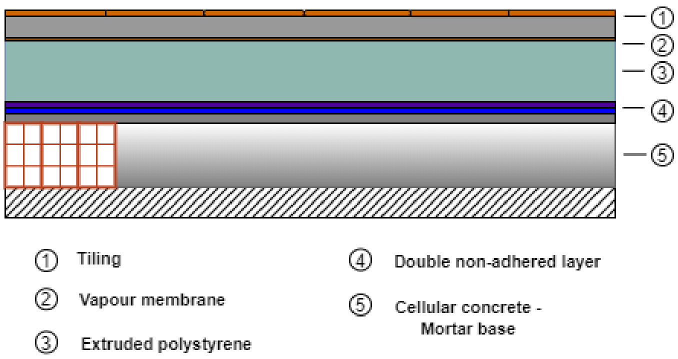
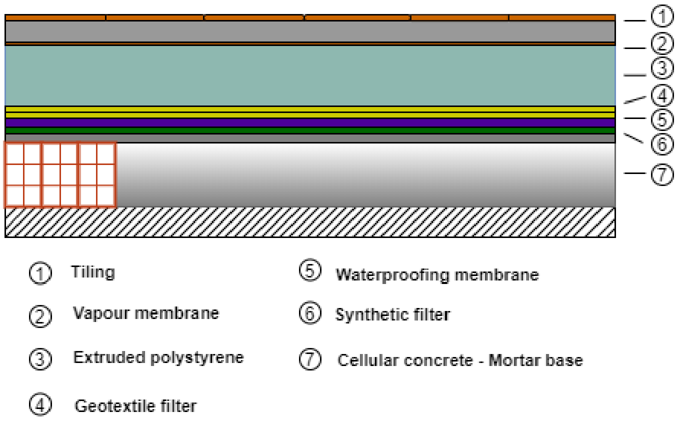
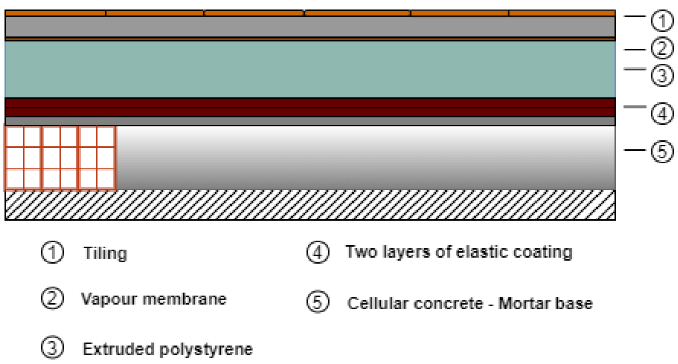
<table>
<tr><th>Type</th><th>Description</th><th>Sections</th></tr>
<tr><td>Bituminous membrane</td><td>Accessible inverted roof consisting of 10 cm of cellular concrete with an average thickness forming slopes, 2 cm of cement mortar base, double non-adhered layer on a sheet of plastomeric bitumen with a 50 g/m² glass fibre felt reinforcement, and another layer of plastomeric bitumen with a 50 g/m² polyethene film reinforcement, bonded to the previous one, thermal insulation of 40 mm thick extruded polystyrene and a 135 g/m² polypropylene vapour membrane.</td><td>
</td></tr>
<tr><td>PVC membrane</td><td>An accessible inverted roof formed by a 10 cm layer of cellular concrete with an average thickness forming slopes, a 2 cm layer of cement mortar for regularisation and a separating layer of geotextile synthetic felt, a 1.20 mm thick waterproofing membrane with PVC and reinforced with glass fibre felt. Two layers of geotextile felt and extruded polystyrene insulation board measuring 40 mm thick and 135g/m² polypropylene vapour membrane.</td><td>
</td></tr>
<tr><td>Elastomeric membrane</td><td>An accessible inverted roof formed by a 10 cm layer of cellular concrete with an average thickness forming slopes, a 2 cm layer of cement mortar for regularisation and a double layer of elastic coating based on copolymers, applied by roller and reinforced between both layers with polypropylene fibre mesh and an insulating plate of extruded polystyrene measuring 40 mm thick with a 135g/m² polypropylene vapour membrane.</td><td>
</td></tr>
</table>

Figure 1: Description of the accessible flat roofs analysed.

The historical data of repairs carried out on the roofs of a sample of 12 public hospitals in Extremadura (Spain) between 2002 and 2017 were analysed. The Public Healthcare Service of Extremadura provided data that were used to contrast the degradation model. They were also used to relate the different states of degradation specified in Table 1 to the different anomalies that affect the correct performance of the membranes. In addition, the data served as a base for identifying their maintenance.

Authors analysed the different degradation states *i* that each membrane could suffer. This state depends only on the last observed condition state. The set of deterioration states that a component can acquire forms the scale of degradation [36]. The scale reflects the deterioration of the component until its failure and has different condition values associated with each state, in a range of 0-100. This allows identifying the state of deterioration of the component in question [37]. State 7 is called the state of failure, and it is where the component is beyond repair. The degradation scale used is shown in Table 1.

Table 1: Scale of degradation of the flat roof membrane.

Degree	**Degradation**	**Condition Range**	**Description**
1	Minimum	> 99	The flat roof membrane is free from defects.
2	Mild	99-92	Slight degradation of some non-critical parts of the roofing membrane that do not affect its service and reliability.
3	Minor	92-85	Minor deterioration of some non-critical parts of the flat roof membrane but may generate a slight reduction in reliability or utility.
4	Notable	85-75	The degradation of the flat roof membrane is moderate. It affects serviceability or reliability but is still adequate.
5	Significant	75-65	The performance of the flat roof membrane is affected by the deterioration of critical and non-critical parts.
6	Major	65-50	Critical parts of the flat roof membrane can be further deteriorated, resulting in a significant loss of reliability or utility.
7	Severe	≤ 50	A severe reduction in utility or reliability may arise, generating a loss of safety. Replacement of the flat roof membrane is only possible.

According to Table 1, the degradation state changes from a faultless condition in state 1 to the collapse of the membranes in state 7. In this last state, the deterioration of the membranes is so severe that they lose their initial properties and a multitude of cracks or detachments appear. This produces water infiltrations that damage the building, affecting the health and safety of the users.

The states of degradation are not directly related to an anomaly, but to its occurrence and severity. Thus, a slight fissure can result in a condition 4 and a multitude of fissures at the singularities cause the state of deterioration to be 6. Cracks and detachments can be caused by structural movements, with internal stresses appearing on the membranes [38], detachment of the membrane with the construction elements the roofing system (drainage, vertical wall, expansion joints,...) [39], efforts generated from the transit of persons or the placement of facilities, membrane deterioration, among others [40]. On the other hand, the loss of properties can be due to ageing, chemicals generated by cleaning or maintenance, the appearance of fungi or microorganisms [41], among others. Also, it includes user claims. These are caused by the loss of the properties and result in the appearance of anomalies.

During the lifetime of a building component, planned maintenance is required to ensure its functionality [42]. This maintenance includes the performance of corrective and preventive maintenance on the roof elements and associated management, cleaning, servicing, repainting, repair and partial replacement of the membranes [43]. Therefore, maintenance operations allow the waterproofing membranes to maintain their properties by keeping moisture from penetrating into the building [44]. According to ISO 15686-1, maintenance is defined as a combination of all technical and associated administrative actions during the service life to retain a building, or its parts, in a state in which it can perform its required functions. It includes cyclical maintenance, reactive condition-based maintenance (repairs to correct defective performance) and major refurbishment [45].

Two types of maintenance were observed on the roofs analysed: corrective and preventive [46]. Corrective maintenance is carried out after the occurrence of a fault, in order to return the element to a state suitable for performing its function, while preventive maintenance aims to mitigate degradation and reduce the probability of failure [47]. The preventive maintenance involved in this study is composed in two parts. The first one is a maintenance with an established periodicity of one year, where cleaning measures of elements carried by the wind, the accumulated sediments are removed and the construction elements related to the sealing are checked. The second one concerns local repairs and replacements required to reduce membrane deterioration and minimize cracking or delamination. Corrective maintenance is based on the complete replacement of the membrane when it reaches the end of its useful life. The partial replacement of the membrane is carried out in zones where the anomalies affect its functionality. Anomalies are more frequently to appear in singular areas, such as connections with vertical walls and drains, near pipes, expansion joints, among others. Therefore, the described maintenance allows the membrane to improve its degradation state.

The probability of the component changing from condition state *i* to condition state *j* in a given time was defined, P_{ij} , to apply the Markov model [48]. These probabilities constitute the transition matrix of the Markov model. The Markov property states that the probability of a future event occurring depends only on the last observed event and not on past events. The condition of the membrane depends only on the last state of degradation observed during the maintenance technician's inspection. Therefore, the state transition probability [49] is determined by Equation (1).

$$P_{ij} = P\left({}^{E_n = j}/_{E_{n-1} = i} \right) \quad (1)$$

Where P_{ij} is the probability of the component passing from state *i* to state *j* and E_n the state vector of the component in the n-th observation.

The transition matrix [P] was obtained by using a history of data collected during past observations [50]. A high amount of observed data is needed for this, as an extensive database is required for subsequent data filtering and for the resulting matrix to be close to the actual deterioration behaviour of the component. The transition matrix for *n* states is represented as:

$$[P] = \begin{bmatrix} P_{11} & P_{12} & \cdot & \cdot & P_{1i} \\ P_{21} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ P_{j1} & \cdot & \cdot & \cdot & P_{ij} \end{bmatrix}$$

The data needed to determine the state transition matrices of the flat roofs analysed were obtained from the study conducted by Grussing [51] in Risk-Based facility management approach for building components using a discrete Markov process - Predicting condition, reliability and remaining service life. A data set with thousands of components was collected through the U.S. Department of Defence Facility Condition Assessment Program and used to generate the degradation matrix. The components of the vector E_n are called $E_n(i)$, which represent the probability of the component being in condition i in observation n. E_0 was defined as the initial state vector of degradation. Whereas the component presents the best state of condition, the initial vector is expressed in Equation (2).

$$E_0 = [1\ 0 \ldots 0] \tag{2}$$

Knowing the degradation state of the component at a given time and its transition matrix, the probabilities of it being in the deterioration states at the next inspection were determined using Equation (3).

$$E_n = E_0 \cdot [P]^n \tag{3}$$

The reliability and life cycle of each of the hospital's critical components or systems must also be obtained to determine the most appropriate maintenance policy for the component studied in this paper [33]. Thus, the optimal maintenance policy to be followed can be designed, so the component does not enter a state that is unsuitable and endangers patients' health, workers' safety or the functionality of the building. Hence, the reliability index, RI was defined as the probability that the degradation state of the analysed component is above the absorption state (from which there is no probability of exiting) in an established period. The absorption vector, *R*, was defined to obtain the index. Such a vector acquires value 1 for the states above failure and 0 when they exceed it [52], according to Equation (4):

$$RI = E_n \cdot R \quad (4)$$

Next, the condition of the three types of membranes was modelled to schedule the periodicity of condition-based maintenance. Condition-based maintenance is a monitored maintenance according to the condition of the system and includes a combination of physical condition assessment, analysis and possible further maintenance actions [47].

The maintenance of the component is thus specified for the next 20 years, and the reliability index of the system after implementing the different possible annual maintenance operations is obtained. This index will have a minimum value, which may not be exceeded, so the maintenance actions must be implemented. Subsequently, probabilistic condition-based techniques of a system were used to determine the equations that governed the model [53].

The random variable T is defined, which represents the useful life of the component to be studied. A Survival (or Reliability) function, *R(t),* is defined, which quantifies the probability that a component is running at the end of time *t*. Also defined is the Failure function, *F(t),* which measures the probability that a component will fail in time *t*. The first follows a negative exponential function, and both are complementary. The random variable *T* has a function *F(t)* of a cumulative distribution defined according to Equation 5:

$$F(t) = \mathrm{P}(T \leq t) \quad (5)$$

The Failure Density Function is derived from the failure function over time. It is defined by Equation (6) and indicates failure probability per time unit:

$$f(t) = \frac{d}{dt}F(t) \quad (6)$$

The hazard function *λ(t)* represents the propensity for a component to fail at the next instant, considering that up to the current one, it has not failed. A formal definition can be reached following this reasoning, which ends in Equation (8). Starting from the conditioned probability that a component fails in a time gap s after the instant t, shown in Equation (7).

$$P(t < T \leq T + s \,/\, T > t) = \frac{P(t < T \leq T + s)}{P(T > t)} = \frac{F(t + s) - F(t)}{R(t)} \quad (7)$$

By dividing this expression by the unit of time s, taking limits and establishing that s tends to zero, Equation (8) is obtained.

$$\lambda(t) = \lim_{s \to 0} \frac{1}{s} \cdot \frac{F(t + s) - F(t)}{R(t)} = \frac{f(t)}{R(t)} \quad (8)$$

The Weibull distribution was used to typify the failure functions, complementary to the reliability function, according to Equation (9).

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (9)$$

Where R is the probability that the roof will be operational in a given time (t), and α and β are dimensionless coefficients that generate the characteristic shape of the curve.

Results

Three maintenance actions determined the most suitable maintenance policy for flat roofs: corrective, preventive and no maintenance. In this way, the preventive maintenance model developed does not include cleaning operations, elimination of sediments or revision of constructive elements that influence watertightness, since these actions are programmed and their periodicity does not have to be estimated. The periodicity of these maintenance operations is established. The frequency of preventive and corrective maintenance is obtained by the Markov model in order to ensure proper degradation of the system under analysis. If the state of degradation of the component does not impair its functionality, no maintenance operations would be carried out. corrective maintenance is defined as a full replacement of the membrane when its functionality cannot be guaranteed. Preventive maintenance includes repair and replacement measures that improve the state of deterioration and preserve the properties of the membrane. For this case, the maximum partial area that can be replaced is 5%. The most appropriate implementation period for these last two maintenance actions should optimise reliability, to reduce the probability that the component is above the state of collapse. Figure 2 shows the corrective and preventive maintenance matrix, $[M]_{Corrective}$ y $[M]_{Preventive}$.

$$[M]_{Corrective} \quad \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad [M]_{Preventive} \quad \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 2: Corrective and preventive maintenance matrix.

The corrective matrix shows how by replacing the component, it recovers to the lowest state of condition, regardless of its state. The preventive matrix reflects what this maintenance action would look like. When the component is between degradation stages 1 and 4 and is repaired, it returns to a degradation state 2. If the component is in state 5 or 6 and is repaired, it returns to a state of deterioration 3 and 4, respectively. Finally, if the component enters the state of failure (7), preventive maintenance operations do not improve the condition state and only the corrective maintenance action can be implemented.

The state transition matrix [P] estimates the probability of the roof remaining in or increasing the last observed condition state after an inspection. These probabilities depend on the roof analysed. Three matrices were used in this study, one for each type of membrane: bitumen, PVC and elastomeric, which are shown in matrix form in Figures 3, Figure 4 and Figure 5.

$$[P]_{bituminous} = \begin{bmatrix} 0.644 & 0.111 & 0.173 & 0{,}004 & 0{,}037 & 0{,}01 & 0{,}02 \\ 0 & 0.823 & 0.102 & 0.034 & 0{,}017 & 0{,}012 & 0{,}012 \\ 0 & 0 & 0.838 & 0.09 & 0.036 & 0{,}013 & 0{,}022 \\ 0 & 0 & 0 & 0.771 & 0.138 & 0.06 & 0{,}032 \\ 0 & 0 & 0 & 0 & 0.836 & 0.119 & 0.044 \\ 0 & 0 & 0 & 0 & 0 & 0.898 & 0.102 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 3: State transition matrix for accessible flat roofs covered with a bituminous membrane [51]

$$[P]_{PVC} = \begin{bmatrix} 0.679 & 0.115 & 0.141 & 0{,}035 & 0{,}018 & 0{,}012 & 0 \\ 0 & 0.829 & 0.089 & 0.027 & 0{,}035 & 0{,}011 & 0{,}01 \\ 0 & 0 & 0.896 & 0.053 & 0.03 & 0{,}006 & 0{,}015 \\ 0 & 0 & 0 & 0.846 & 0.091 & 0.034 & 0{,}029 \\ 0 & 0 & 0 & 0 & 0.91 & 0.063 & 0.027 \\ 0 & 0 & 0 & 0 & 0 & 0.931 & 0.069 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 4: State transition matrix for accessible flat roofs covered with a PVC membrane [51]

$$[P]_{Elastomeric} = \begin{bmatrix} 0.692 & 0.1334 & 0.114 & 0{,}0135 & 0{,}0232 & 0{,}0104 & 0{,}0135 \\ 0 & 0.8132 & 0.1104 & 0.0343 & 0{,}019 & 0{,}0126 & 0{,}0106 \\ 0 & 0 & 0.8576 & 0.0823 & 0.027 & 0{,}0138 & 0{,}0193 \\ 0 & 0 & 0 & 0.8304 & 0.1018 & 0.0429 & 0{,}0249 \\ 0 & 0 & 0 & 0 & 0.8619 & 0.1002 & 0.0379 \\ 0 & 0 & 0 & 0 & 0 & 0.9101 & 0.0899 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 5: State transition matrix for accessible flat roofs covered with an elastomeric membrane [51]

Another condition imposed is that membrane cannot return to a more favourable state of degradation without being subject to the required maintenance operations. Besides, the probability of remaining in a state is always higher than the probability of transitioning from that state. The maintenance matrix [M] will depend on the maintenance policy selected. Thus, Equation (3) is transformed into Equation (10).

$$E_n = E_0 \cdot [M] \cdot [P]^n \qquad (10)$$

The model assumes that the system degrades *n* time intervals and that corrective and preventive maintenance is performed once in this period. In addition, the selected maintenance is carried out at the end of the *n* periods analysed. Therefore, solving Equation (10) gives the probability that the component is in each of the defined degradation states. In order to implement more than one maintenance operation at different intervals, first the value of the state vector E_n with maintenance in period *n* is calculated. Then, the value of the state vector in a higher period, E_{n+x}, where the initial state vector corresponds to the previous state vector E_n. Thus, the necessary maintenance could be implemented at the end of the $n+x$ interval.

The membrane studied were considered in the best state of condition. Five possible scenarios were assumed to establish the minimum value of the reliability index. In the first three scenarios, this parameter for each type of roof has to be higher than 80%, 75% and 63.21%, respectively, and no preventive maintenance is implemented. In the last two scenarios, reliability was assumed to be higher than 63.21% and, also, in these two scenarios, one and two preventive maintenance operations were implemented, respectively. The reliability value of 63.21% corresponds to the characteristic life of a component according to the Weibull distribution. The values of 80% and 75% were established to determine the influence of reliability on the determination of maintenance periodicity and service life. Thus, the influence of membrane reliability and preventive maintenance was determined to analyse the life of the roofs. Table 2, Table 3 and Table 4 shows the results obtained for the three types of roofs and the five possible scenarios.

Table 2: Maintenance policies for the bituminous membrane roof over 20-year horizon

Maintenance operations of the bituminous membrane roof										
Year	R>80%		R>75%		R>63.21%		R>63.21%/1PM		R>63.21%/2PM	
	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)
1	N	97.9	N	97.9	N	97.9	N	97.9	N	97.9
2	N	95.7	N	95.7	N	95.7	N	95.7	N	95.7
3	N	93.4	N	93.4	N	93.4	N	93.4	N	93.4
4	N	91	N	91	N	91	N	91	N	91
5	N	88.4	N	88.4	N	88.4	N	88.4	N	88.4
6	N	85.6	N	85.6	N	85.6	N	85.6	N	85.6
7	N	82.7	N	82.7	N	82.7	P	85.6	P	85.6
8	C	97.9	N	79.7	N	79.7	N	84.3	N	84.3
9	N	95.7	N	76.5	N	76.5	N	82.7	N	82.7
10	N	93.4	C	97.9	N	73.3	N	80.8	N	80.8
11	N	91	N	95.7	N	70	N	78.6	N	78.6
12	N	88.4	N	93.4	N	66.7	N	76.31	P	78.6
13	N	85.6	N	91	N	63.3	N	73.8	N	77.5
14	N	82.7	N	88.4	C	97.9	N	71.1	N	76
15	C	97.9	N	85.6	N	95.7	N	68.4	N	74.4
16	N	95.7	N	82.7	N	93.4	N	65.5	N	72.5
17	N	93.4	N	79.7	N	91	C	97.9	N	70.4
18	N	91	N	76.5	N	88.4	N	95.7	N	68.2
19	N	88.4	C	97.9	N	85.6	N	93.4	N	65.8
20	N	85.6	N	95.7	N	82.7	N	91	N	63.3

N: No maintenance operations; C: Corrective maintenance; P: Preventive maintenance; Op: Operation; R: Reliability; 1PM: One action of preventive maintenance; 2PM: Two action of preventive maintenance

Table 3: Maintenance policies for the PVC membrane roof over a 20-year horizon

Maintenance operations of the PVC membrane roof										
Year	R>80%		R>75%		R>63.21%		R>63.21%/1PM		R>63.21%/2PM	
	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)
1	N	100	N	100	N	100	N	100	N	100
2	N	99.4	N	99.4	N	99.4	N	99.4	N	99.4
3	N	98.5	N	98.5	N	98.5	N	98.5	N	98.5
4	N	97.2	N	97.2	N	97.2	N	97.2	N	97.2
5	N	95.7	N	95.7	N	95.7	N	95.7	N	95.7
6	N	93.9	N	93.9	N	93.9	N	93.9	N	93.9
7	N	92	N	92	N	92	N	92	P	93.9
8	N	90	N	90	N	90	N	90	N	92.9
9	N	87.9	N	87.9	N	87.9	N	87.9	N	91.6
10	N	85.7	N	85.7	N	85.7	P	87.9	N	90.2
11	N	83.5	N	83.5	N	83.5	N	86.4	N	88.6
12	N	81.1	N	81.1	N	81.1	N	85.5	N	86.9
13	C	100	N	78.8	N	78.8	N	84.1	N	85.1
14	N	99.4	N	76.4	N	76.4	N	82.6	N	83.2
15	N	98.5	C	100	N	74	N	80.9	N	81.2
16	N	97.2	N	99.4	N	71.6	N	79.1	N	79.1
17	N	95.7	N	98.5	N	69.2	N	77.3	N	77
18	N	93.9	N	97.2	N	66.8	N	75.4	P	77
19	N	92	N	95.7	N	64.4	N	73.4	N	76
20	N	90	N	93.9	C	100	N	71.3	N	74.8

N: No maintenance operations; C: Corrective maintenance; P: Preventive maintenance; Op: Operation; R: Reliability; 1PM: One action of preventive maintenance; 2PM: Two action of preventive maintenance

Table 4: Maintenance policies for the elastomeric membrane roof over a 20-year horizon

Maintenance operations of the elastomeric membrane roof										
Year	R>80%		R>75%		R>63.21%		R>63.21%/1PM		R>63.21%/2PM	
	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)	Op	R (%)
1	N	98.6	N	98.6	N	98.6	N	98.6	N	98.6
2	N	97.1	N	97.1	N	97.1	N	97.1	N	97.1
3	N	95.4	N	95.4	N	95.4	N	95.4	N	95.4
4	N	93.6	N	93.6	N	93.6	N	93.6	N	93.6
5	N	91.6	N	91.6	N	91.6	N	91.6	N	91.6
6	N	89.4	N	89.4	N	89.4	N	89.4	N	89.4
7	N	87	N	87	N	87	N	87	N	87
8	N	84.6	N	84.6	N	84.6	N	84.6	P	87
9	N	82	N	82	N	82	P	84.6	N	85.9
10	C	98.6	N	79.3	N	79.3	N	83.4	N	84.5
11	N	97.1	N	76.6	N	76.6	N	82	N	82.9
12	N	95.4	C	98.6	N	73.8	N	80.4	N	81.1
13	N	93.6	N	97.1	N	70.9	N	78.6	N	79.1
14	N	91.6	N	95.4	N	68	N	76.7	P	79.1
15	N	89.4	N	93.6	N	65.1	N	74.6	N	78.1
16	N	87	N	91.6	C	98.6	N	72.3	N	76.8
17	N	84.6	N	89.4	N	97.1	N	70	N	75.4
18	N	82	N	87	N	95.4	N	67.6	N	73.7
19	C	98.6	N	84.6	N	93.6	N	65.1	N	72

20	N	97.1	N	82	N	91.6	F	98.6	N	70

N: No maintenance operations; C: Corrective maintenance; P: Preventive maintenance; Op: Operation; R: Reliability; 1PM: One action of preventive maintenance; 2PM: Two action of preventive maintenance

On the one hand, the period of preventive maintenance was determined through an iterative process that optimizes the reliability of the system, increasing the probability that the analysed membranes do not fall into the state of collapse. On the other hand, corrective maintenance is performed when the reliability of the system is below the minimum value set for each scenario.

Implementing preventive maintenance was found to increase the reliability of the system, and the replacement of the roofing membrane can be delayed. As the scenario analysed is less reliable, the year in which the membrane is replaced increases. The minimum reliability studied is 63.21%. Above this value, there is no guarantee that the functionality of the membrane will not be affected and consequently the membrane will reach the end of its life. At the end of the service life the complete replacement of the membrane is necessary. The results show that the most appropriate scenario implements two preventive maintenance operations, and the membrane's reliability value does drop below 63.21%. The PVC membrane roof suffers the least degradation and, therefore, its replacement can be delayed.

The authors also analysed the evolution of the reliability of the three types of roofs over time to compare their deterioration. Figure 6 shows the survival curves obtained.

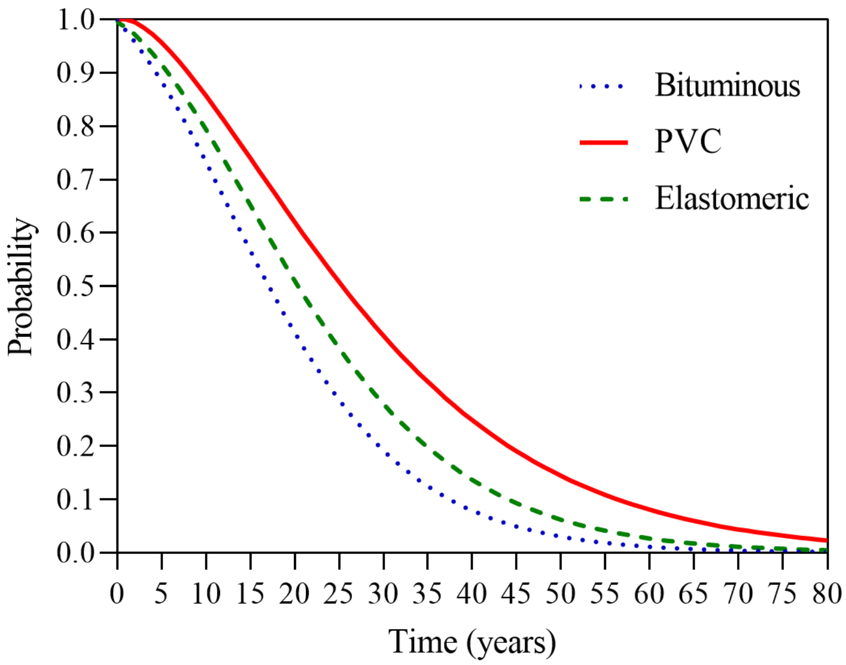


Figure 6: Survival function of the roofing membranes over time.

PVC membrane roofs were also the most likely to be operational in a given time, whereas in bituminous roofs, the probability decreases more rapidly. The complete maintenance of the PVC membranes is carried out in a longer time interval than that of the elastomeric and bituminous membranes, as indicated in the 5 scenarios presented in Table 2, Table 3 and Table 4. For example, in 75% reliability scenario with no preventive maintenance operations, full membrane replacement is performed in year 15, 12 and 10 for PVC, elastomeric and bituminous membranes, respectively. Based on Figure 6, the parameters α and β of the Weibull distribution for the three types of membrane analysed (bituminous, PVC and elastomeric) were obtained and characterised in Equation (11), Equation (12) and Equation (13).

$$R(t) = e^{-\left(\frac{t}{22}\right)^{1.52}} \tag{11}$$

$$R(t) = e^{-\left(\frac{t}{32}\right)^{1.52}} \tag{12}$$

$$R(t) = e^{-\left(\frac{t}{25}\right)^{1.52}} \tag{13}$$

Where R is the probability of failure of each flat roof membrane, and t is the time to failure expressed in years. The density failure function was analysed by type of roofing membrane as a function of time. This function is defined according to Equation (6) and has been plotted in Figure 7.

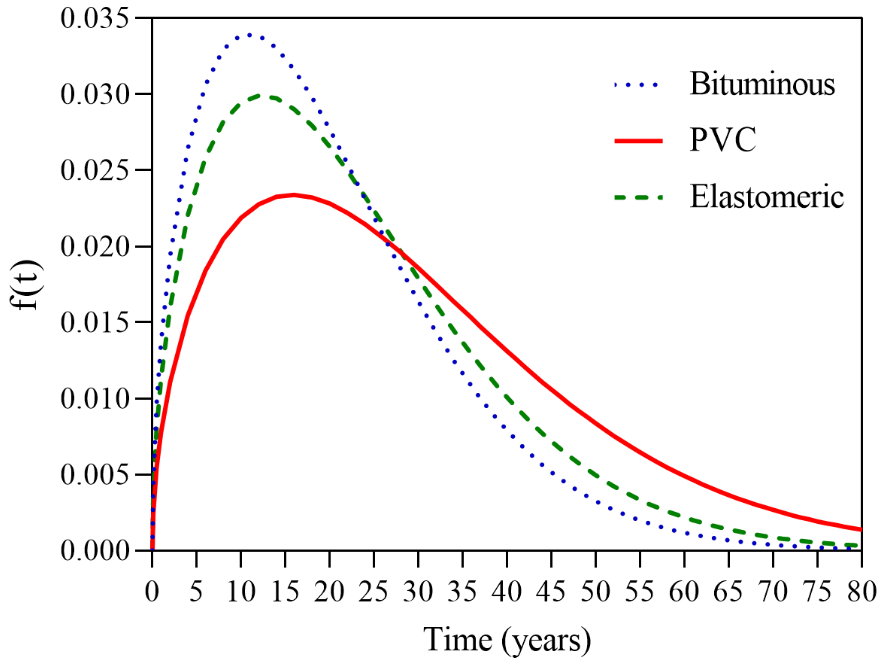


Figure 7: The Failure Density Function of the roofs over time.

The probability of failure occurring was determined to calculate the standard life of roof membranes as a function of the likelihood they will be operational in a given time, as shown in Figure 8.

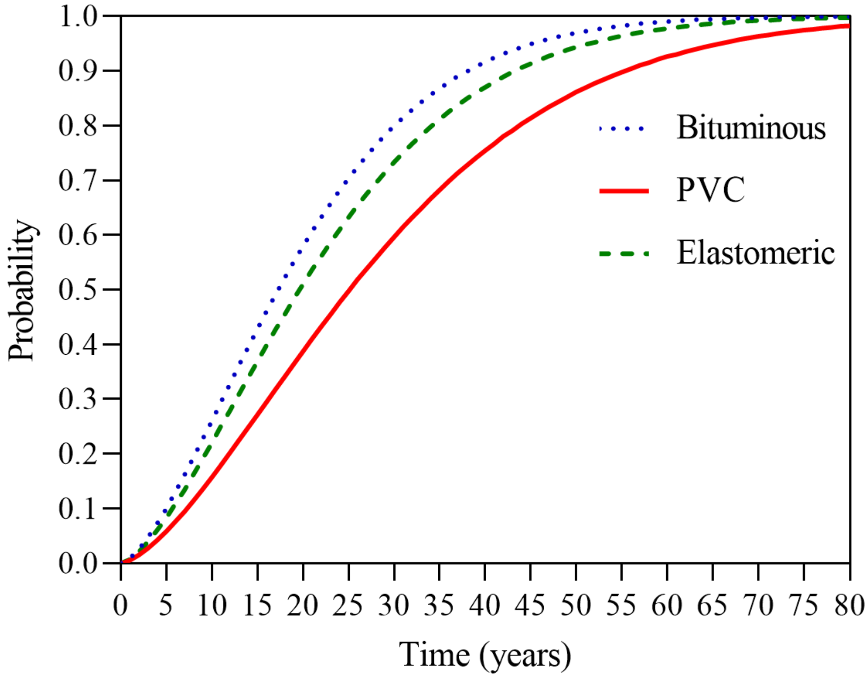


Figure 8: Failure function of the roofing membranes over time

Table 5 shows the operating life of the membrane for the three types of roofs based on the failure function in Figure 8.

Table 5: Standard accessible flat roof membrane life

	Standard life (years)		
Reliability (%)	Bituminous	PVC	Elastomeric
80	8	13	10
75	10	14	11
70	11.5	16	13
65	13	18	15
63.2	13.5	19	16
60	14	20	16

The authors studied the replacement time of the waterproofing membranes while evaluating the condition of the roofs analysed in this paper. The analysis was conducted for the five scenarios defined above and allowed for planning the maintenance of the roofs already built with a simple inspection to determine the degradation of the membrane. This ensures that the roofs in use do not fail and that they perform their function with adequate reliability. Table 6 shows the replacement time of the roof depending on the initial state of degradation, the membrane and the scenario.

Table 6: Replacement time of the membrane according to its initial state of degradation

	Degradation	80%	75%	63.21%	63.21%/1M	63.21%/2M
PVC Membrane	1	13	15	20	24	28
	2	12	14	19	24	27
	3	11	13	18	23	26
	4	7	9	13	17	23
	5	7	9	12	16	23
	6	4	5	7	12	15
	7	1	1	1	1	1
Bituminous membrane	1	8	10	14	17	21
	2	9	11	14	18	21
	3	7	9	12	16	20
	4	6	7	9	15	18
	5	4	5	8	13	17
	6	3	3	5	9	13
	7	1	1	1	1	1
Elastomeric membrane	1	10	12	16	20	24
	2	10	12	16	20	24
	3	9	10	14	19	23
	4	7	8	11	16	22
	5	5	6	9	14	19
	6	3	4	5	11	15
	7	1	1	1	1	1

The authors found that if a membrane is in the state of failure (7), it must be replaced during the same year, regardless of the scenario or type of membrane. The year in which the replacement must be made is specified for the remaining stages of condition. Finally, Figure 9 shows the failure rate for each type of membrane, calculated using equation (8), where the density function is divided by the survival function, complementary to the equations (11), (12) and (13).

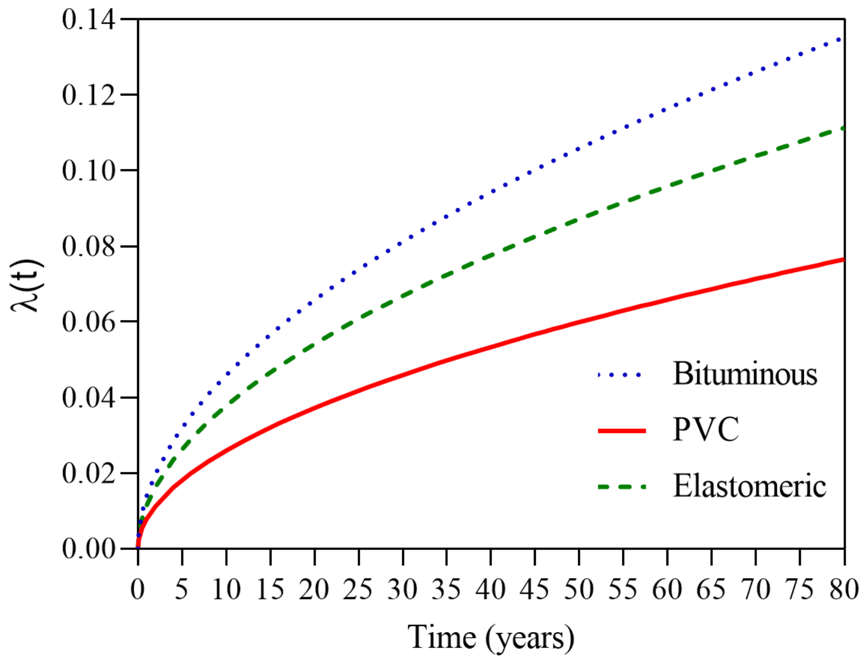


Figure 9: Roof failure rate over time

The failure rate increases in all the roofs analysed. Bituminous membrane, have the steepest slope, resulting in the highest number of failures over time and the shortest operating life. Nevertheless, PVC membrane have the lowest number of failures over time and a longer life span.

Discussion

The increasing degree of complexity of hospitals and their facilities requires implementing an appropriate methodology for the management of the building's life cycle [54]. It was found that by applying Markov chains to plan the maintenance of the roofs, the most appropriate time for the replacement of the waterproofing membranes could be determined. Thus, maintenance operations keep the component's state of deterioration above the state of failure, with adequate reliability. Therefore, Markov chains can be useful towards efficiently planning the maintenance of the roofs, minimising the risks of component failure and controlling the cost of operations [52].

The authors found that maintenance operations could be systematised according to the initial state of degradation of the flat roof membrane, without compromising its operability. On the other hand, maintenance actions planning helps reduce the cost of this activity compared of unscheduled maintenance. Moreover, the scheduled maintenance decreases the risk of roof failure, which is essential in hospitals, since the appearance of anomalies in the roof can lead to operational malfunctions of buildings [55].

The results show that roofs with PVC membranes can stay in operation for longer, ensuring their reliability. This membrane can be replaced at least four years later than the other layers tested. Although this roof is slightly more expensive, its reliability positions it as a good alternative. However, PVC membrane emits 51% more kg of CO_2 per m^2 in its manufacture and installation than bituminous membrane [21]. Bituminous roofs have the lowest environmental impact, whereas elastomeric roofs have the highest.

Elasticity prevents the diaphragms of the flat roofs from breaking, which avoids failures [56]. Bituminous membranes have low elasticity independent of the ambient temperature. PVC membranes are highly flexible and are highly resistant to traction and breakage, as they are reinforced with a fibreglass mesh and additives to improve their resistance to the weather conditions. Preventive maintenance has also been found to be vital in reducing the degradation of flat roofs [22].

Godfried *et al*. [36] described the Markov model for estimating the performance and maintenance cost of a building roof and Santos *et al.* [57] identified problems involving the current state of the roofs, but none proposed a method for determining maintenance. In this study, a maintenance schedule was proposed that considerably increases the lifetime of the membranes.

The results obtained in Table 5 show that the useful life of the PCV, bituminous and elastomeric membranes is 20, 14 and 16 years respectively. Coffelt *et al.* [34] determined that the period of useful life until the roof reaches the worst state of condition is 21 years. The variation between this result and those obtained in this analysis may be due to the differences between the degradation scales and the roofs observed in the Markov model, the type of membrane and the method of obtaining the service life. In addition, the service life of this study is evaluated based on reliability, so that the membranes do not reach the state of collapse.

While other authors determine maintenance priorities based on four criteria (environmental aggressiveness, level of deterioration, extent and severity of the defect) [55] or choose maintenance activities to reduce total costs and increase performance [58], this research establishes a maintenance schedule based on the condition of the membranes. In this way, priority is given to ensuring that the condition of hospital membranes does not collapse as opposed to the cost of maintenance.

The preventive maintenance focused on repair and replacing partially of parts the membrane that were in poor condition [59]. With this in mind, maintenance and inspection operations must be logged, and the functionality of the system must be guaranteed throughout its life cycle [60]. The repair of the waterproofing must be carried out by specialized technicians [61]. However, the resources used during maintenance operations can considerably increase the environmental impact of the roofs [62].

Inspection and diagnosis have proven to be necessary to standardise and systematise procedures within a proactive maintenance strategy to prevent flat roof anomalies. For this purpose, non-destructive methods [63] and various renovation techniques are available on site to maintain and/or restore the functional properties of flat roofs [64]. Similarly, it is advisable to carry out periodic maintenance audits to determine whether the management of the assets in the building is adequate and to forecast the evolution of the demand for maintenance [65]. Most of the polymeric layers that make up a roof are incompatible with each other, so there may be interactions and incompatibilities between some of these elements [66]. Therefore, it is vital to separate them with auxiliary layers that prevent contact. The weather conditions of the area where the building is located must also be considered, for their significant influence on roof deterioration [67]. This is reflected in the system degradation matrices, and by estimating it, one can adapt and prevent the roofs from failing.

Future work should aim at studying the factors influencing the maintenance of flat roofs to obtain more indicators and determine the best maintenance policy. This methodology can also be applied to other buildings of similar characteristics and evaluate the convenience of implementing green roofs from the perspective of their maintenance [68].

This research is useful to define and protocol the maintenance operations, determining the optimal time to perform the replacement and repair operations, allowing to maintain the reliability of the system during all its service life. It also allows for more precise annual maintenance budgets.

Conclusions

Applying Markov chains to estimate the degradation of hospital flat roofs enables optimising maintenance operations and increasing the reliability of the system during its service life. The authors found that with this stochastic model, maintenance of flat roofs can be planned, which minimises costs and damage from failure and breakage. Thus, the functionality of the flat roofs studied in this paper is guaranteed throughout their operational life, reducing anomalies.

The most appropriate time for the replacement of the membrane was estimated by determining their degradation status during the last inspection. This made it possible to plan the maintenance of the roofs in operation during their useful life, considering their reliability. The importance of preventive maintenance was also demonstrated along with how it increases operating life by 40% for PVC roofs and by 50% for bituminous and elastomeric roofs. The results showed that PVC membranes are the least degraded. They have an operating life of 28 years for an excellent initial condition, four and seven years longer than elastomeric and bituminous roofs, respectively. The life span of the flat roof membrane increases as the minimum reliability required decreases, and preventive maintenance increases. The authors also found that accessible flat roofs with PVC membrane need less preventive maintenance, followed by elastomeric membrane and finally, bituminous membrane.

This paper proposes a tool based on historical data that can be simply updated and can be easily extended to other roof components or building construction elements. The data set analysed does not consider factors such as the quality and execution of the construction.

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