A quantitative analysis on the feasibility of 4D Planning Graphic Systems *versus* Conventional Systems in building projects

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ABSTRACT

Poor planning of building projects is observed to definitely increase both time consumption and costs. Limitations of existing studies about contrast between BIM 4D methodology and conventional graphic planning, focus on comparing them from a qualitative point of view, without quantifying their real performance. The present paper is aimed at performing a quantitative analysis on BIM 4D methodology as compared to conventional graphic planning. Provided this novel methodology accounts for building elements including technical and visual information, subsequent construction operations would be carried out in a more controlled and a more accurate environment. In particular, a balance between suitable construction data management included in the BIM model and appropriate use of task planning information was analysed. The results show that the integration of BIM in the project execution planning ensures greater control over the model, thus preventing time- and cost-inefficiencies along the project development. Although traditional planning proves to be 20% shorter than 4D simulation, the latter is observed to be 40% more efficient regarding visual monitoring of time progress and also 40% more efficient in the data update process.

Keywords: sustainable projects; Building Information Modeling (BIM); scheduling; planning; 4D.

1. INTRODUCTION

Current building projects show increasing requirements regarding scope and complexity. As a consequence, the use of appropriate tools involving productivity, safety, health and organization is strongly advised in order to ensure that all operations in a specific project are carried out in a coordinated manner (*Locatelli et al., 2014*). The relevance of social sustainability in residential and commercial buildings was explored by *Tayyab (2017)*. Moreover, the lack of efficient project planning has elsewhere been identified as a common cause of substantial time and money loss, as well as of an increasing rate of work-related accidents (*Won et al., 2016*).

Frequent problems regarding building project arising from weak connectivity between design and construction due to inefficiencies in the transfer of information involving both phases have also been reported (*Hardin et al., 2015*).

The Building Information Modeling (BIM) methodology is a project technique which regards information as a key relevant factor throughout the project life cycle by elaborating a database where each element has associated visualization attributes and related attached information, like for instance building materials, technical characteristics, constructions costs, etc. (*Boton et al., 2015*). BIM is therefore a good asset not only in the project design stage, but also in the subsequent construction stage, provided it ensures working effectiveness and time saving along the project life cycle (*Eadie et al., 2013*).

Although BIM is a powerful planning tool which will definitively improve project execution, it must be complemented with specific planning software packages (*Chen, 2014*) devoted to control execution tasks, which are developed by setting an appropriate time period and the interdependence pattern among them (*Stylianou et al., 2016*).

Han et al. (2015) have recently reported on work control by analysing the deviations between a point cloud -generated with a laser scan- and 4D BIM. They concluded that the proposed classification mechanism increased the effectiveness of the BIM model with lower levels of development (LoD), thus allowing visual evaluation of progress information at the operational level.

Additionally, *Koo and Fischer (2000)* analysed 4D planning viability through a case study. They concluded that 4D models are a useful alternative to project scheduling tools like CPM networks and bar charts. They enable users to quickly understand a schedule and to identify potential problems. In the same line of research, *Heesom et al. (2004)* proposed a model to determine the usage requirements for each of the various applications of 4D CAD simulations.

Also, *Han and Golparvar-Fard (2015)* developed a classification method to control deviations in construction at the operational level, based on the comparison of the 3D model with the point cloud. They sorted materials by textures and colours to further assign such classification to each 3D model element in order to compare textures and colours of the 3D model elements with those of the point cloud. The authors concluded that this methodology showed 95.9% accuracy when applied to the monitoring of the construction progress.

Jongeling and Olofsson (2007) presented a process method for the planning of work-flow by combined use of location-based scheduling and 4D CAD. They suggested that a location-based approach to 4D CAD might improve the usability of this model for work-flow analyses.

Moon et al. (2014) used 4D to detect project contradictions by applying the results to the case study in order to evaluate practical applications and feasibility of the developed system.

They concluded that the results of a project can be improved by a 4D analysis system. Nevertheless, they did not attempt quantification of the obtained results.

On another note, *Smith (2016)* identified the successful practices, procedures, and strategies that companies are implementing in relation to cost management through BIM. Their results slowed that the surveyed companies were spending significant time and effort on the handling of quality and breadth in BIM models, due to restricted access to models as well as to compatibility problems between software and standards. Also, *Farzad (2015)* described a methodology that integrates BIM with the green building certification system LEED. In particular, they explained how this integration could assist project teams in promoting sustainability. However, again, the results were not appropriately measured and quantified.

Kim et al. (2015) presented a methodology that adapts to the time-scale metrics of large-scale developments. Such procedure proved that an automatic evaluation and visualization of integrated development scenarios and their metrics can be achieved. Finally, *Zhang et al. (2011)* developed a 4D building information model according to the general analysis and management of conflicts and safety issues during construction. Based on this model, they studied the integration of dynamic analysis of time dependent structures, conflict analysis and scheduling / resource / cost management and dynamic detection of collisions of facilities. The results provided a feasible methodology for BIM-based applications. However, none of these authors compared traditional planning systems with 4D simulation, in order to quantify their potential and usability.

The present work is aimed at analysing in a quantitative manner the feasibility of 4D planning graphical systems *versus* conventional ones, also accounting for a pros and cons assessment as compared to conventional planning in building projects.

2. METHODOLOGY

A total of 65 architecture/engineering companies in the field of the construction sector were surveyed for the purpose stated in the present work, 33 out of which were finally selected as they proved: *(i)* to achieve previous experience in conventional planning for project execution (52 out of 65) and *(ii)* to use BIM as the working methodology for project progress (33 out of 65).

These companies started to develop project planning with the 4D simulation methodology, and the results have been compared to the conventional planning methodology. The following software packages were used to run the 4D simulation:

- Design software: *Autodesk Revit* 2015, used to build up the BIM model containing all the building elements involved in the 4D simulation, each of which had previously been featured by specific characteristic parameters, i.e. element category, base level, horizontal 4D and vertical 4D.
- Planning software: *Microsoft Project* 2013, used to create the various tasks involved in the material execution of the building, each of which had previously been defined in terms of duration and interdependence with the remaining ones, thus giving rise to the Gantt diagram that would subsequently monitor the execution of the works.
- Construction management software: *Autodesk Navisworks Manage* 2015, used to generate the virtual survey of the construction by dealing with the parameterized BIM model and with the list of tasks organized in the Gantt diagram.

As for planning software packages, there are two complementary categories: pre-planning and 4D planning. The former was used to define the various activities linked to the project execution, whereas the latter served to combine the BIM model with the defined tasks so that a virtual survey of the construction was generated (the so-called *4D simulation*). The interrelation between the abovementioned packages is pictured in Figure 1:

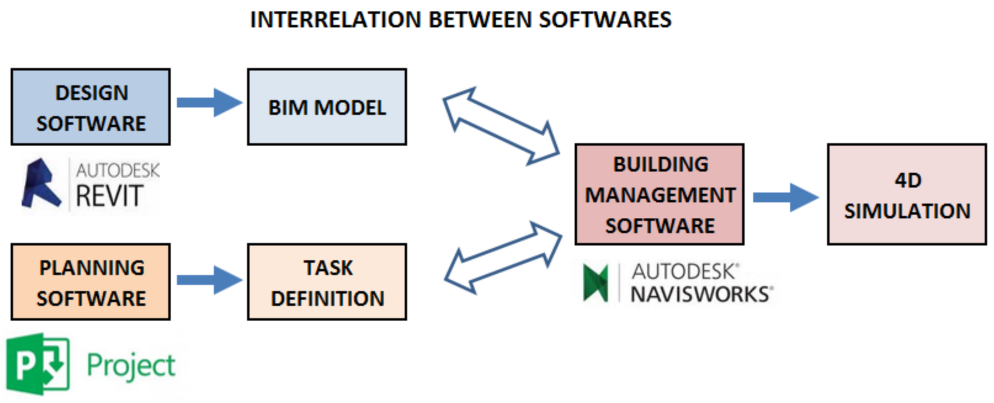


FIG. 1. Connection between the software packages used for the study.

As previously stated, the design software needed the construction elements to be featured according to the following specific parameters:

- Element category: the parameter accounting for the nature of the element (*Charette et al.,* 1999), like for instance wall, canopy, beam, column, turnbuckle, etc.
- Horizontal 4D and vertical 4D: the parameters that refer to the position of the construction element in the plane, so that the floor, a column, a beam, a retaining wall… are featured to be lying on the *x* axis (horizontal 4D) or on the *y* axis (vertical 4D).
- Base level: the parameter that sets the position of the element on the *z* axis.

Once the elements were parameterized, each task involved in the construction process was set according to the planning software, i.e. by having previously identified duration and interconnection with the remaining tasks. Finally, a time diagram to monitor the project execution was set.

After the parametrization of the construction elements in the design software and the task definition in the planning software, a virtual simulation of the construction process was implemented by the construction management software. The corresponding BIM model elements were associated to each task, also filtering the elements by the previously defined parameters (element category, base level, horizontal 4D and vertical 4D).

Once the temporal data and the construction elements were supplied as inputs, monitoring and control of the construction process were carried out by updating such information. At that point, the purpose was to run the 4D simulation in order to analyse the planned task status as compared to the actual one according to the following steps:

- Establish a baseline containing the initial planning dates.
- Update the planning file with actual progress on site.
- Update the link between planning software and construction management software.
- Run the 4D simulation to compare planned- and actual- construction progress.

Figure 2 shows the different stages of the referred 4D planning and the monitoring and control phases. The left picture stands for the three activities that conform the 4D project planning phase as detailed in their actual sequence, whereas the right picture illustrates the four stages that conform project monitoring and control phase. Note the iterative character of both phases is emphasized by the half-circle shaped arrows.

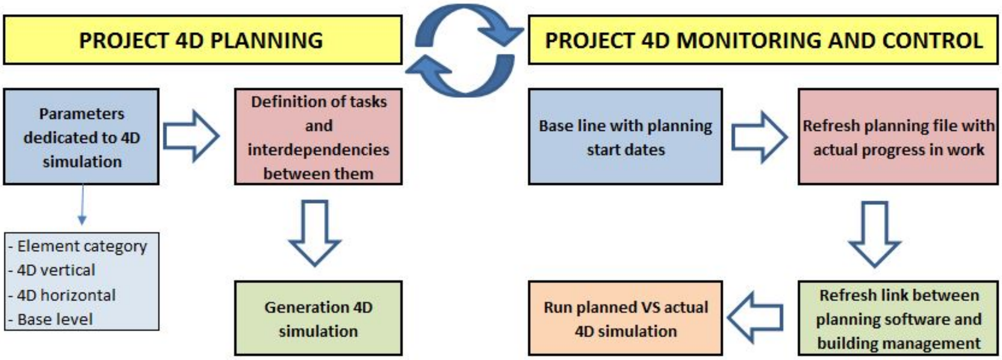


FIG. 2. Diagrams for the project planning (left) and the project monitoring and control (right) phases.

3. CASE STUDY

The methodology described in the preceding section was applied to a project planning regarding the execution of a specific building structure. The building is located in Badajoz (Spain) and was designed for standard office use with a reinforced concrete structure based on columns, beams and slabs. As for its geometry, the building has two underground floors, a ground floor and four raised floors, 700 m^2 (18.30 x 38.30 m) floor area each. The structure under study was designed and modelled as pictured in Figure 3 and included the following components:

- Foundation: including by micropiles and foundation walls.
- Vertical structure: vertical columns distributed along the 4 floors of the building.
- Horizontal structure: horizontal beams that support the slabs of the 4 floors of the building.

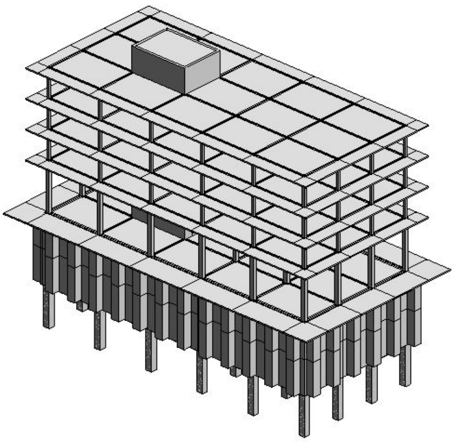


FIG. 3. 3D plot of the project structure under study.

Figures 4 and 5 illustrates the definition of the various parameters for each structural element in the BIM model. A structural column was selected on the ground floor of the concrete building (HA-25, section 450 x 450 mm and height 2.5 m), whose featuring parameters –as those of the remaining structural elements- were set as input for the 4D simulation. Figure 4 shows the *assembly code* parameter, which identifies the element category, and Figure 5 illustrates the Horizontal 4D and Vertical 4D parameters of the abovementioned column.

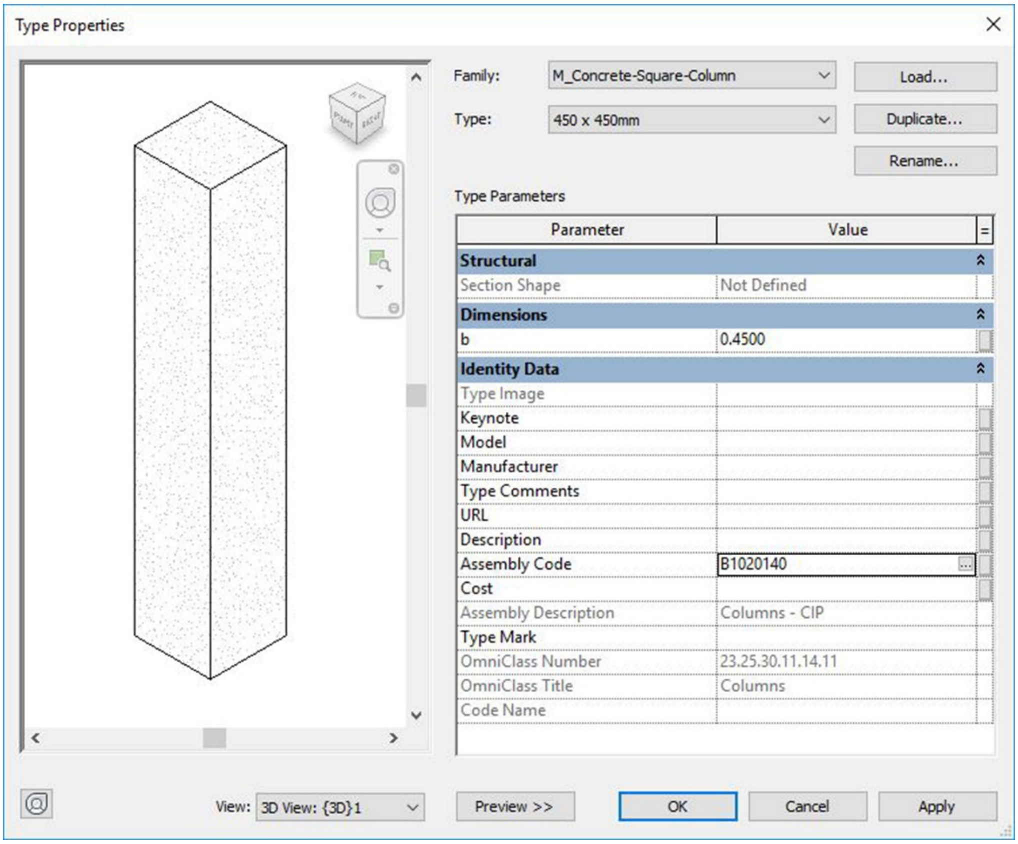


FIG. 4. Element category parameters of a 450x450 mm column.

Figure 4 accounts for the values of the parameters of *M-Concrete_Square_Column* element type, i.e. the column width (0.45 m) and the assembly code. Such code refers to the element category parameter, which represents the nature of the element according to the standard UNIFORMAT II classification for building elements (*Charette et al.,* 1999).

The horizontal 4D and vertical 4D parameters identify the various elements included in the model, and they are referred to the *x* and *y* axes, respectively, so that vertical 4D characterizes the element's location as referred to height (1, 2, 3, etc.) and the horizontal 4D features the element's location as referred to the horizontal plane (A, B, C, D, etc.).

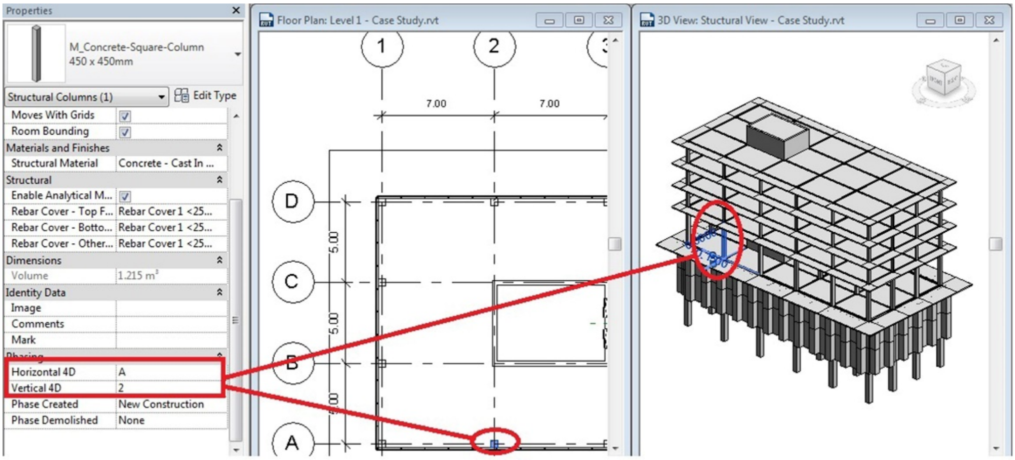


FIG. 5. Horizontal 4D and vertical 4D parameters.

Figure 5 stands for the values of the horizontal 4D and vertical 4D parameters for the selected *M-Concrete_Square_Column* element, both in floor plan as in 3D. Location for a given element was therefore parametrized by a letter-number code, so that a code grid accounted for the location of the whole set of elements.

A task temporal planning corresponding to the structure execution was also designed. For the sake of an appropriate definition, duration and interdependencies were previously determined for each task.

Figure 6 lists the various tasks that conformed the project execution. It can be observed that the project execution corresponds to the construction of different floors, from that of the foundation up to highest (5^{th}) one, all according to the three following levels:

- Level 1: floor in the building.

- Level 2: element category according to its nature (foundation, pillar, slab, etc.).
- Level 3: operation zone in a given floor (v1, v2, v3, etc.).

In addition, each level was set to account for several operation zones (like for instance the foundation level, which was divided into six ones), each of which had previously been identified with an expected execution period as well as with the corresponding starting and completion dates of performance.

Foundation	**12 days**	**Tue 03/05/16**	**Wed 18/05/16**
C_foun_v1	2 days	Tue 03/05/16	Wed 04/05/16
C_foun_v2	2 days	Thu 05/05/16	Fri 06/05/16
C_foun_v3	2 days	Mon 09/05/16	Tue 10/05/16
C_foun_v4	2 days	Wed 11/05/16	Thu 12/05/16
C_foun_v5	2 days	Fri 13/05/16	Mon 16/05/16
C_foun_v6	2 days	Tue 17/05/16	Wed 18/05/16
Level -2	**12.75 days**	**Thu 19/05/16**	**Mon 06/06/16**
Level -1	**26 days**	**Fri 20/05/16**	**Mon 27/06/16**
Level 1	**77.25 days**	**Tue 07/06/16**	**Thu 22/09/16**
Level 2	**28.75 days**	**Thu 09/06/16**	**Wed 20/07/16**
Level 3	**27 days**	**Fri 01/07/16**	**Tue 09/08/16**
Level 4	**27 days**	**Thu 21/07/16**	**Mon 29/08/16**
Level 5	**18 days**	**Thu 11/08/16**	**Mon 05/09/16**
Terrain and Excavations	**134.5 days**	**Mon 18/04/16**	**Fri 21/10/16**
Doors of Lifts	**35 days**	**Fri 02/09/16**	**Fri 21/10/16**
Courtain walls and Partitions	**35 days**	**Thu 01/09/16**	**Thu 20/10/16**

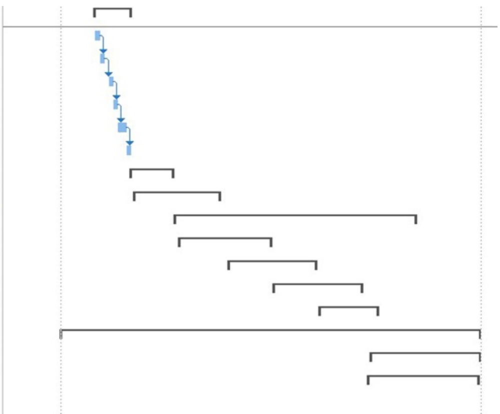


FIG. 6. Temporal planning as related to task definition.

Finally, the definition of the parameters involved for each structural element together with the task planning resulted in the 4D simulation and the subsequent virtual surveying of the structure. A snapshot of such 4D simulation is shown in Figure 7, which illustrates a virtual surveying sequence of the building structure arising from the information included in the BIM model (involving parametric definition of element category, base level, horizontal 4D and vertical 4D) as well as in the task planning software package (tasks sequence involving starting/concluding dates and interconnections among them).

Note elements in grey represent those which are expected to have been concluded at the particular instant of the execution snapshot, whereas elements in green stand for those for which execution is supposed to be in progress. Of course, elements whose execution had not yet been started would be non-visible. For the particular case in Figure 7, for instance, both foundation floors (-1 and -2), as well as part of floor 1, had already been completed; moreover, four pillars in floor 1 are represented to be in progress.

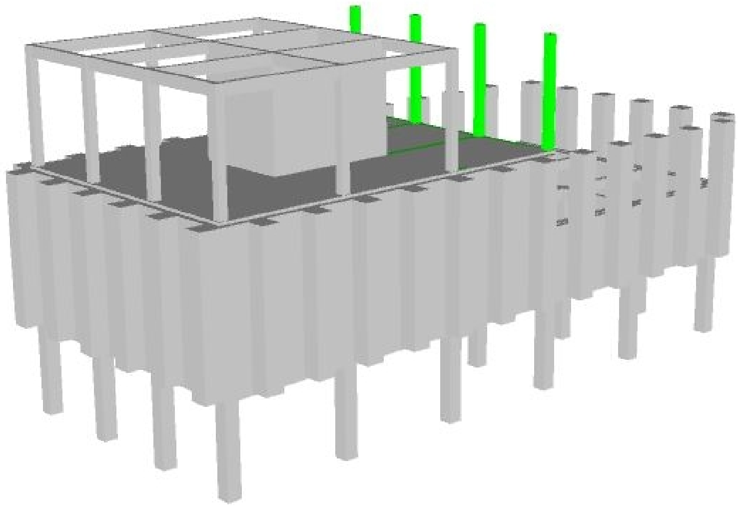
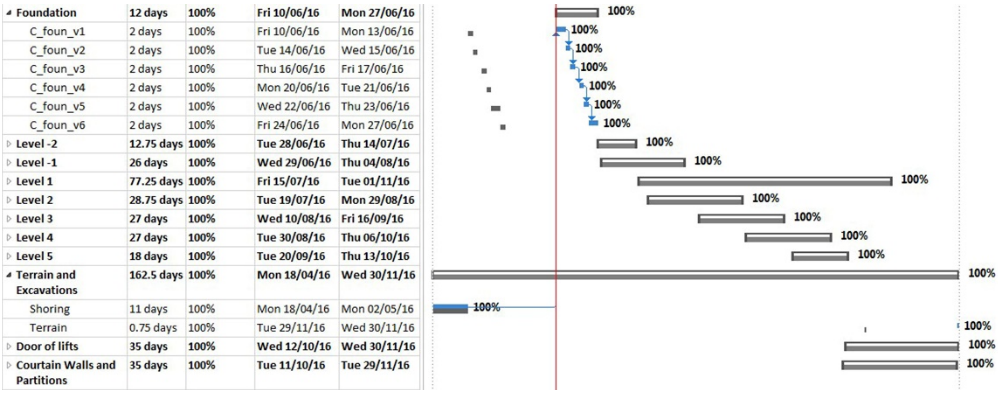


FIG. 7. 4D project simulation.

Figure 8 illustrates a temporal delay in the execution stage, so that a general horizontal displacement as related to the red time-reference line is accomplished. Such time delay is accounted for in the planning software at an initial stage. Finally, a couple of joint snapshots of the structure survey according to the abovementioned colour code are shown in Figure 9. Elements in grey are those which had already been completed, whereas those in green are the elements which had not been completed yet -but indeed should had if no delay had been achieved-. This way, the visualization of potential execution delays at any instant, and moreover the consequences on the remaining tasks, are ensured.



Foundation	12 days	100%	Fri 10/06/16	Mon 27/06/16
C_foun_v1	2 days	100%	Fri 10/06/16	Mon 13/06/16
C_foun_v2	2 days	100%	Tue 14/06/16	Wed 15/06/16
C_foun_v3	2 days	100%	Thu 16/06/16	Fri 17/06/16
C_foun_v4	2 days	100%	Mon 20/06/16	Tue 21/06/16
C_foun_v5	2 days	100%	Wed 22/06/16	Thu 23/06/16
C_foun_v6	2 days	100%	Fri 24/06/16	Mon 27/06/16
Level -2	12.75 days	100%	Tue 28/06/16	Thu 14/07/16
Level -1	26 days	100%	Wed 29/06/16	Thu 04/08/16
Level 1	77.25 days	100%	Fri 15/07/16	Tue 01/11/16
Level 2	28.75 days	100%	Tue 19/07/16	Mon 29/08/16
Level 3	27 days	100%	Wed 10/08/16	Fri 16/09/16
Level 4	27 days	100%	Tue 30/08/16	Thu 06/10/16
Level 5	18 days	100%	Tue 20/09/16	Thu 13/10/16
Terrain and Excavations	162.5 days	100%	Mon 18/04/16	Wed 30/11/16
Shoring	11 days	100%	Mon 18/04/16	Mon 02/05/16
Terrain	0.75 days	100%	Tue 29/11/16	Wed 30/11/16
Door of lifts	35 days	100%	Wed 12/10/16	Wed 30/11/16
Courtain Walls and Partitions	35 days	100%	Tue 11/10/16	Tue 29/11/16

FIG. 8. Actual task-status update in temporal planning.

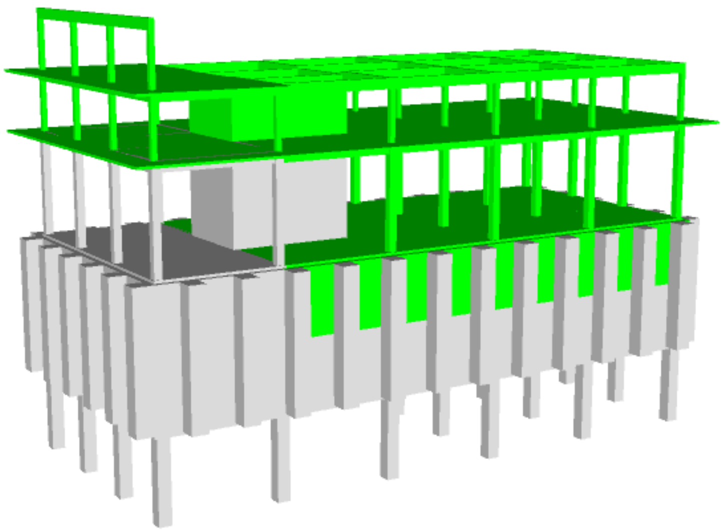


FIG. 9. Planned 4D simulation *vs* actual 4D simulation.

In sum, the structure's planning phase allowed a detailed virtual visualization of the execution progress based on the input featuring parameters of the BIM model and of the time planning software. Subsequently, a 4D simulation to set a comparison between the planning phase and the actual construction phase was carried out so that deviations between the planned and the actual tasks were straightforwardly identified.

Table 1 accounts for a comparison between traditional planning and 4D simulation through a variable-based assessment. For this specific purpose, the person in charge of each company involved in the present study completed the information of columns *Conventional, 4D* and *Weighting* (variables) for each of the factors in the first column, always accounting for the following concerns:

- *Conventional* and *4D* columns: numerical value ranging from 1 (*unsatisfactory*) to 5 (*optimal*).
- *Weighting* column: percentage parametrizing relevance of the particular factor as compared to the remaining ones.

Values from the 33 companies were averaged as listed below. Traditional planning in project execution (rated 3.10) was seen to be less efficient than 4D simulation (rated 4.00). However, conventional planning was less time-consuming than 4D simulation (rated 4 out of 5 as compared to 3 out of 5, respectively), whereas 4D simulation was significantly more effective than traditional planning in terms of progress' visual monitoring and change management (rated 4 as compared to 2, respectively).

Variable	Conventional	4D	Weighting	Weighted Conventional	Weighted 4D
Execution time	4	3	10%	0.40	0.30
Planning difficulty	3	4	5%	0.15	0.20
Information viewing	2	4	10%	0.20	0.40
Documentation use ease in the office	4	4	5%	0.20	0.20
Documentation use ease in field	4	3	10%	0.40	0.30
Understanding documentation	3	4	5%	0.15	0.20
Information quantity and organization	3	5	10%	0.30	0. 50
Change management and control	2	4	10%	0.20	0.40

Possibility of optimizing work performance	3	4	10%	0.30	0.40
Extraction of planning reports and ratios	4	2	5%	0.20	0.10
Updating ease	3	5	20%	0.60	1.00
TOTALS	35	43	100%	3.10	4.00

Table 1. Comparison between traditional planning and 4D simulation.

On another note, the simple data updating allowed by 4D simulation was an interesting point, as all the BIM information depends on parameters values. Information updating was therefore based on editing these parameter values.

4. DISCUSSION

The Standish Group 2015 Chaos Report surveyed around 50,000 projects worldwide between 2011 and 2015 (*Hastie et al.,* 2015). The authors regarded as *successful* any project which met the planned time and budget, and accordingly reported the concluding data listed in Table 2. As it can be seen, the rate of projects that were delayed and exceeded the expected cost approached 50%. In this sense, 4D simulation definitely provide a valuable graphical tool not only for architects and engineers but also for contractors, subcontractors and suppliers.

	2011	**2012**	**2013**	**2014**	**2015**
Successful	29%	27%	31%	28%	29%
Challenged	49%	56%	50%	55%	52%
Failed	22%	17%	19%	17%	19%

Table 2. Quantification of *successful*, *challenged* and *failed* projects along the period 2011-2015 according to criteria reported by *Hastie et al.* 2015.

Also, project simulations would therefore ensure a better monitoring and understanding to stakeholders. In addition, if any disagreement from a project agent about duration or interdependences of activities is accounted for, 4D simulation might certainly serve to other stakeholders to make a clear decision on any particular issue.

Time planning is an activity which shows inherent difficulties and therefore lacks easy handling, provided it involves potential changing scenarios. However, planning tools can be used by stakeholders as a sort of information centre to account for their knowledge and experience. As an overall purpose, 4D simulation is aimed at achieving an accurate time planning, thus providing the client with reliable information on the actual duration and costs of a given project. The key advantage of planning programs lies in their ability to simultaneously manage a large number of tasks linked to time slots as well as to ensure appropriate scheduling update, thus ensuring accurate monitoring of the project progress.

Visual building planning through the implementation of task sequencing can help contractors and subcontractors understand the degree of completion of the project, and hence clarify the scope of the involved tasks. In sum, this graphical tool is intended to make information more intuitive and therefore to supplement some other widely accepted and more powerful planning methodologies like for instance PERT, CPM, ROY, *Precedences*, *Tense Flow*, *Links*, etc.

5. CONCLUSIONS

The 4D simulation procedure reported along the present manuscript has proved to increase the efficiency in the planning process of construction projects. The average ratings achieved for the various involved items were computed as 3.1 and 4.1 for the temporal planning and the

4D simulation, respectively –as referred to a score interval ranging from 1, *unsatisfactory*, up to 5, *optimal*-.

Traditional planning was observed to be less time-consuming –as much as 20%- than the 4D simulation method (rated 4 out of 5 as compared to 3 out of 5, respectively). However, the 4D simulation was seen to be significantly more effective than traditional planning in terms of progress' visual monitoring and control (rated 4 as compared to 2, respectively); in particular, 4D simulation improvement in terms of visual control was quantified as 40% higher as compared to conventional planning.

On another note, virtual visualization of the building execution phase in the 4D simulation definitely helped improve the understanding of the construction process. Such degree of clarification was quantified as 20% higher than for the case of conventional planning, which would definitely provide stakeholders with a better understanding on the construction progress and would therefore help them make appropriate decisions at an earlier stage (hence with no drastic implications on forthcoming stages of the project).

With regard to the ease for information updating, 4D simulation were observed to be 40% more efficient than conventional planning, which is justified by the fact that updating in 4D simulation involves a mere change in the values of the parameters implemented in the BIM model or in the planning software.

As a final point, it should be noted that the larger the project, the less efficient manual planning becomes since the involved information would not entirely be under control. However, the application of BIM technology to task planning is definitely an appropriate choice for the sake of clarity, organization and ease of handling of the execution scheduling.

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Highlights

The integration of BIM in the project execution planning ensures greater control over the model, preventing time- and cost-inefficiencies.

4D simulation is 40% more efficient regarding visual monitoring of time progress, 40% more efficient in the data update process and 40% more efficient than conventional planning for information updating.

Traditional planning is 20% shorter than 4D simulation.

Larger the project, the less efficient manual planning because the involved information would not be under control.

A quantitative analysis on the feasibility of 4D Planning Graphic Systems *versus* Conventional Systems in building projects

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ABSTRACT

Poor planning of building projects is observed to definitely increase both time consumption and costs. Limitations of existing studies about contrast between BIM 4D methodology and conventional graphic planning, focus on comparing them from a qualitative point of view, without quantifying their real performance. The present paper is aimed at performing a quantitative analysis on BIM 4D methodology as compared to conventional graphic planning. Provided this novel methodology accounts for building elements including technical and visual information, subsequent construction operations would be carried out in a more controlled and a more accurate environment. In particular, a balance between suitable construction data management included in the BIM model and appropriate use of task planning information was analysed. The results show that the integration of BIM in the project execution planning ensures greater control over the model, thus preventing time- and cost-inefficiencies along the project development. Although traditional planning proves to be 20% shorter than 4D simulation, the latter is observed to be 40% more efficient regarding visual monitoring of time progress and also 40% more efficient in the data update process.

Keywords: sustainable projects; Building Information Modeling (BIM); scheduling; planning; 4D.

1. INTRODUCTION

Current building projects show increasing requirements regarding scope and complexity. As a consequence, the use of appropriate tools involving productivity, safety, health and organization is strongly advised in order to ensure that all operations in a specific project are carried out in a coordinated manner (*Locatelli et al., 2014*). The relevance of social sustainability in residential and commercial buildings was explored by *Tayyab (2017)*. Moreover, the lack of efficient project planning has elsewhere been identified as a common cause of substantial time and money loss, as well as of an increasing rate of work-related accidents (*Won et al., 2016*).

Frequent problems regarding building project arising from weak connectivity between design and construction due to inefficiencies in the transfer of information involving both phases have also been reported (*Hardin et al., 2015*).

The Building Information Modeling (BIM) methodology is a project technique which regards information as a key relevant factor throughout the project life cycle by elaborating a database where each element has associated visualization attributes and related attached information, like for instance building materials, technical characteristics, constructions costs, etc. (*Boton et al., 2015*). BIM is therefore a good asset not only in the project design stage, but also in the subsequent construction stage, provided it ensures working effectiveness and time saving along the project life cycle (*Eadie et al., 2013*).

Although BIM is a powerful planning tool which will definitively improve project execution, it must be complemented with specific planning software packages (*Chen, 2014*) devoted to control execution tasks, which are developed by setting an appropriate time period and the interdependence pattern among them (*Stylianou et al., 2016*).

Han et al. (2015) have recently reported on work control by analysing the deviations between a point cloud -generated with a laser scan- and 4D BIM. They concluded that the proposed classification mechanism increased the effectiveness of the BIM model with lower levels of development (LoD), thus allowing visual evaluation of progress information at the operational level.

Additionally, *Koo and Fischer (2000)* analysed 4D planning viability through a case study. They concluded that 4D models are a useful alternative to project scheduling tools like CPM networks and bar charts. They enable users to quickly understand a schedule and to identify potential problems. In the same line of research, *Heesom et al. (2004)* proposed a model to determine the usage requirements for each of the various applications of 4D CAD simulations.

Also, *Han and Golparvar-Fard (2015)* developed a classification method to control deviations in construction at the operational level, based on the comparison of the 3D model with the point cloud. They sorted materials by textures and colours to further assign such classification to each 3D model element in order to compare textures and colours of the 3D model elements with those of the point cloud. The authors concluded that this methodology showed 95.9% accuracy when applied to the monitoring of the construction progress.

Jongeling and Olofsson (2007) presented a process method for the planning of work-flow by combined use of location-based scheduling and 4D CAD. They suggested that a location-based approach to 4D CAD might improve the usability of this model for work-flow analyses.

Moon et al. (2014) used 4D to detect project contradictions by applying the results to the case study in order to evaluate practical applications and feasibility of the developed system.

They concluded that the results of a project can be improved by a 4D analysis system. Nevertheless, they did not attempt quantification of the obtained results.

On another note, *Smith (2016)* identified the successful practices, procedures, and strategies that companies are implementing in relation to cost management through BIM. Their results slowed that the surveyed companies were spending significant time and effort on the handling of quality and breadth in BIM models, due to restricted access to models as well as to compatibility problems between software and standards. Also, *Farzad (2015)* described a methodology that integrates BIM with the green building certification system LEED. In particular, they explained how this integration could assist project teams in promoting sustainability. However, again, the results were not appropriately measured and quantified.

Kim et al. (2015) presented a methodology that adapts to the time-scale metrics of large-scale developments. Such procedure proved that an automatic evaluation and visualization of integrated development scenarios and their metrics can be achieved. Finally, *Zhang et al. (2011)* developed a 4D building information model according to the general analysis and management of conflicts and safety issues during construction. Based on this model, they studied the integration of dynamic analysis of time dependent structures, conflict analysis and scheduling / resource / cost management and dynamic detection of collisions of facilities. The results provided a feasible methodology for BIM-based applications. However, none of these authors compared traditional planning systems with 4D simulation, in order to quantify their potential and usability.

The present work is aimed at analysing in a quantitative manner the feasibility of 4D planning graphical systems *versus* conventional ones, also accounting for a pros and cons assessment as compared to conventional planning in building projects.

2. METHODOLOGY

A total of 65 architecture/engineering companies in the field of the construction sector were surveyed for the purpose stated in the present work, 33 out of which were finally selected as they proved: *(i)* to achieve previous experience in conventional planning for project execution (52 out of 65) and *(ii)* to use BIM as the working methodology for project progress (33 out of 65).

These companies started to develop project planning with the 4D simulation methodology, and the results have been compared to the conventional planning methodology. The following software packages were used to run the 4D simulation:

- Design software: *Autodesk Revit* 2015, used to build up the BIM model containing all the building elements involved in the 4D simulation, each of which had previously been featured by specific characteristic parameters, i.e. element category, base level, horizontal 4D and vertical 4D.
- Planning software: *Microsoft Project* 2013, used to create the various tasks involved in the material execution of the building, each of which had previously been defined in terms of duration and interdependence with the remaining ones, thus giving rise to the Gantt diagram that would subsequently monitor the execution of the works.
- Construction management software: *Autodesk Navisworks Manage* 2015, used to generate the virtual survey of the construction by dealing with the parameterized BIM model and with the list of tasks organized in the Gantt diagram.

As for planning software packages, there are two complementary categories: pre-planning and 4D planning. The former was used to define the various activities linked to the project execution, whereas the latter served to combine the BIM model with the defined tasks so that a virtual survey of the construction was generated (the so-called *4D simulation*). The interrelation between the abovementioned packages is pictured in Figure 1:

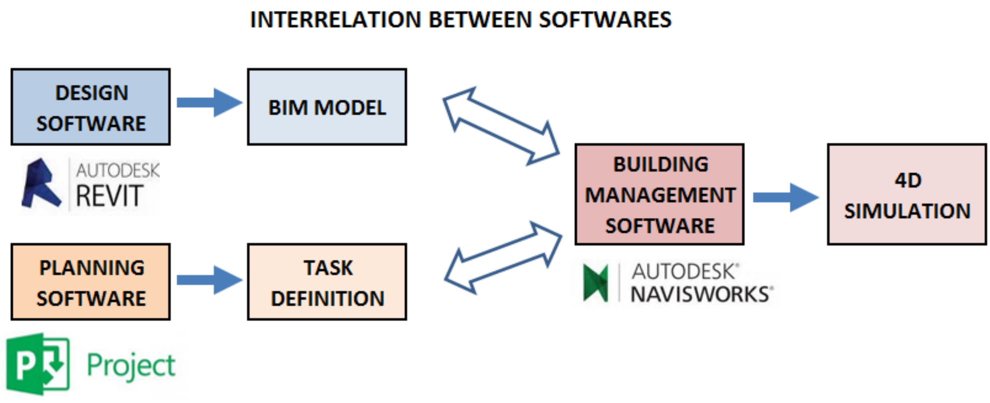

FIG. 1. Connection between the software packages used for the study.

As previously stated, the design software needed the construction elements to be featured according to the following specific parameters:

- Element category: the parameter accounting for the nature of the element (*Charette et al.,* 1999), like for instance wall, canopy, beam, column, turnbuckle, etc.
- Horizontal 4D and vertical 4D: the parameters that refer to the position of the construction element in the plane, so that the floor, a column, a beam, a retaining wall… are featured to be lying on the x axis (horizontal 4D) or on the y axis (vertical 4D).
- Base level: the parameter that sets the position of the element on the z axis.

Once the elements were parameterized, each task involved in the construction process was set according to the planning software, i.e. by having previously identified duration and interconnection with the remaining tasks. Finally, a time diagram to monitor the project execution was set.

After the parametrization of the construction elements in the design software and the task definition in the planning software, a virtual simulation of the construction process was implemented by the construction management software. The corresponding BIM model elements were associated to each task, also filtering the elements by the previously defined parameters (element category, base level, horizontal 4D and vertical 4D).

Once the temporal data and the construction elements were supplied as inputs, monitoring and control of the construction process were carried out by updating such information. At that point, the purpose was to run the 4D simulation in order to analyse the planned task status as compared to the actual one according to the following steps:

- Establish a baseline containing the initial planning dates.
- Update the planning file with actual progress on site.
- Update the link between planning software and construction management software.
- Run the 4D simulation to compare planned- and actual- construction progress.

Figure 2 shows the different stages of the referred 4D planning and the monitoring and control phases. The left picture stands for the three activities that conform the 4D project planning phase as detailed in their actual sequence, whereas the right picture illustrates the four stages that conform project monitoring and control phase. Note the iterative character of both phases is emphasized by the half-circle shaped arrows.

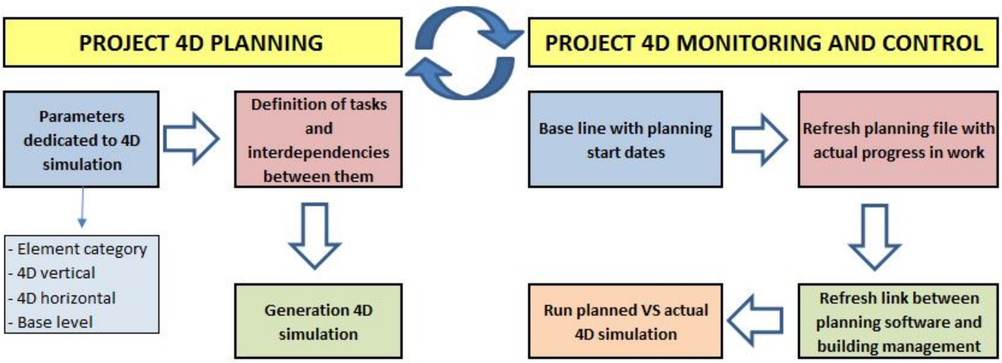

FIG. 2. Diagrams for the project planning (left) and the project monitoring and control (right) phases.

3. CASE STUDY

The methodology described in the preceding section was applied to a project planning regarding the execution of a specific building structure. The building is located in Badajoz (Spain) and was designed for standard office use with a reinforced concrete structure based on columns, beams and slabs. As for its geometry, the building has two underground floors, a ground floor and four raised floors, 700 m^2 (18.30 x 38.30 m) floor area each. The structure under study was designed and modelled as pictured in Figure 3 and included the following components:

- Foundation: including by micropiles and foundation walls.
- Vertical structure: vertical columns distributed along the 4 floors of the building.
- Horizontal structure: horizontal beams that support the slabs of the 4 floors of the building.

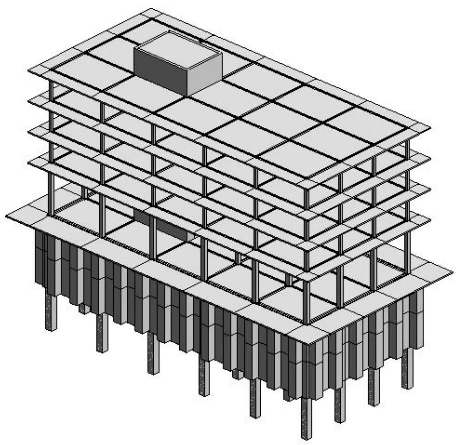

FIG. 3. 3D plot of the project structure under study.

Figures 4 and 5 illustrates the definition of the various parameters for each structural element in the BIM model. A structural column was selected on the ground floor of the concrete building (HA-25, section 450 x 450 mm and height 2.5 m), whose featuring parameters –as those of the remaining structural elements- were set as input for the 4D simulation. Figure 4 shows the *assembly code* parameter, which identifies the element category, and Figure 5 illustrates the Horizontal 4D and Vertical 4D parameters of the abovementioned column.

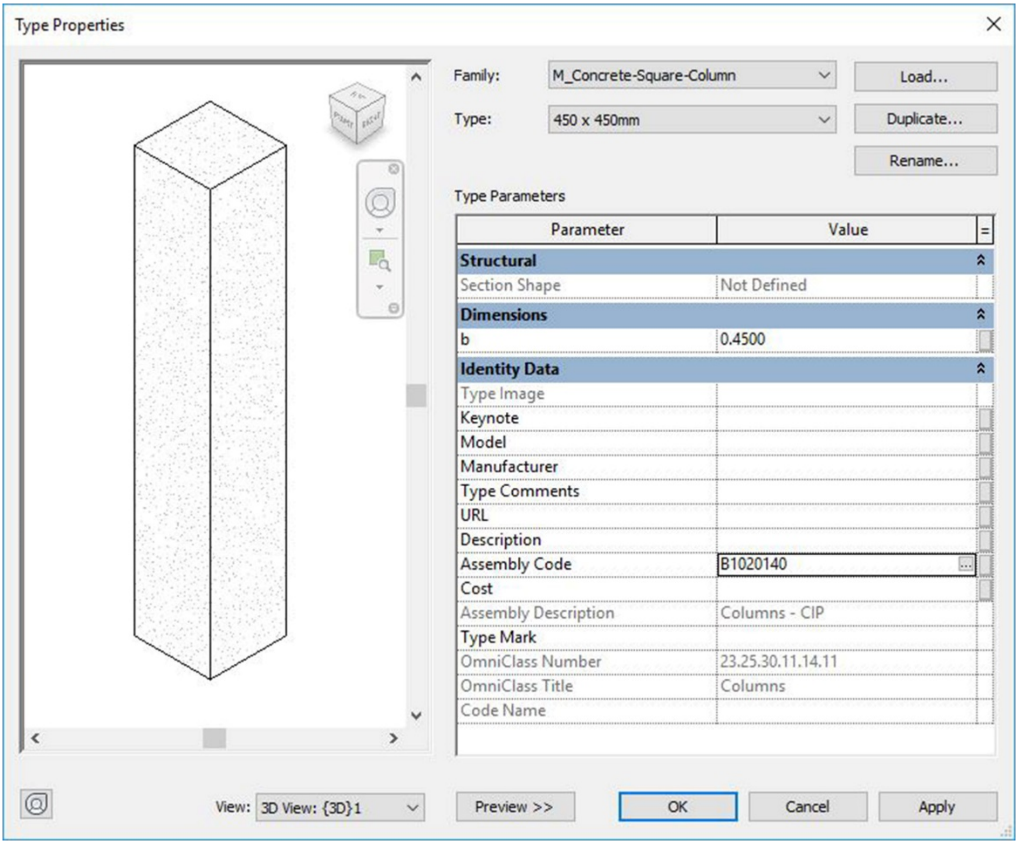

FIG. 4. Element category parameters of a 450x450 mm column.

Figure 4 accounts for the values of the parameters of *M-Concrete_Square_Column* element type, i.e. the column width (0.45 m) and the assembly code. Such code refers to the element category parameter, which represents the nature of the element according to the standard UNIFORMAT II classification for building elements (*Charette et al.,* 1999).

The horizontal 4D and vertical 4D parameters identify the various elements included in the model, and they are referred to the *x* and *y* axes, respectively, so that vertical 4D characterizes the element's location as referred to height (1, 2, 3, etc.) and the horizontal 4D features the element's location as referred to the horizontal plane (A, B, C, D, etc.).

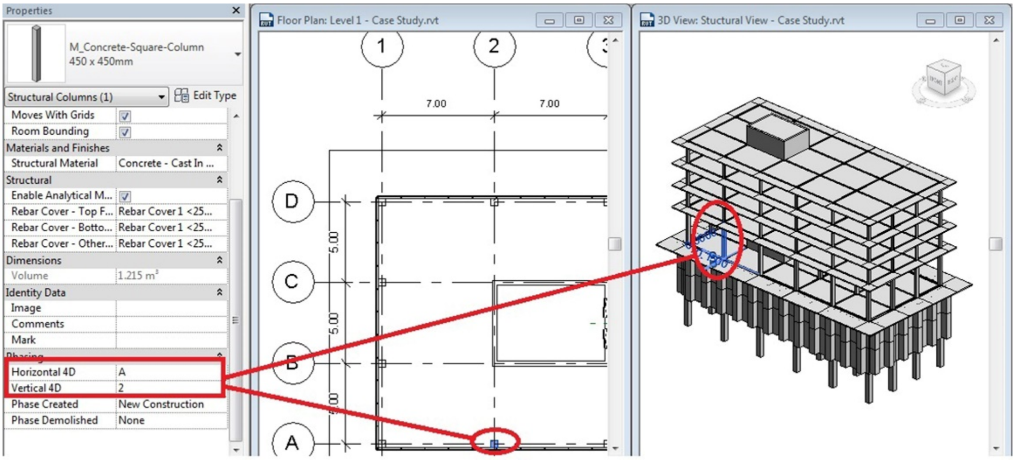

FIG. 5. Horizontal 4D and vertical 4D parameters.

Figure 5 stands for the values of the horizontal 4D and vertical 4D parameters for the selected *M-Concrete_Square_Column* element, both in floor plan as in 3D. Location for a given element was therefore parametrized by a letter-number code, so that a code grid accounted for the location of the whole set of elements.

A task temporal planning corresponding to the structure execution was also designed. For the sake of an appropriate definition, duration and interdependencies were previously determined for each task.

Figure 6 lists the various tasks that conformed the project execution. It can be observed that the project execution corresponds to the construction of different floors, from that of the foundation up to highest (5th) one, all according to the three following levels:

- Level 1: floor in the building.

- Level 2: element category according to its nature (foundation, pillar, slab, etc.).
- Level 3: operation zone in a given floor (v1, v2, v3, etc.).

In addition, each level was set to account for several operation zones (like for instance the foundation level, which was divided into six ones), each of which had previously been identified with an expected execution period as well as with the corresponding starting and completion dates of performance.

Foundation	**12 days**	**Tue 03/05/16**	**Wed 18/05/16**
C_foun_v1	2 days	Tue 03/05/16	Wed 04/05/16
C_foun_v2	2 days	Thu 05/05/16	Fri 06/05/16
C_foun_v3	2 days	Mon 09/05/16	Tue 10/05/16
C_foun_v4	2 days	Wed 11/05/16	Thu 12/05/16
C_foun_v5	2 days	Fri 13/05/16	Mon 16/05/16
C_foun_v6	2 days	Tue 17/05/16	Wed 18/05/16
Level -2	**12.75 days**	**Thu 19/05/16**	**Mon 06/06/16**
Level -1	**26 days**	**Fri 20/05/16**	**Mon 27/06/16**
Level 1	**77.25 days**	**Tue 07/06/16**	**Thu 22/09/16**
Level 2	**28.75 days**	**Thu 09/06/16**	**Wed 20/07/16**
Level 3	**27 days**	**Fri 01/07/16**	**Tue 09/08/16**
Level 4	**27 days**	**Thu 21/07/16**	**Mon 29/08/16**
Level 5	**18 days**	**Thu 11/08/16**	**Mon 05/09/16**
Terrain and Excavations	**134.5 days**	**Mon 18/04/16**	**Fri 21/10/16**
Doors of Lifts	**35 days**	**Fri 02/09/16**	**Fri 21/10/16**
Courtain walls and Partitions	**35 days**	**Thu 01/09/16**	**Thu 20/10/16**

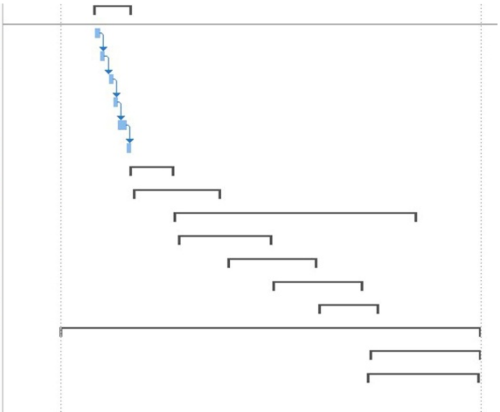

FIG. 6. Temporal planning as related to task definition.

Finally, the definition of the parameters involved for each structural element together with the task planning resulted in the 4D simulation and the subsequent virtual surveying of the structure. A snapshot of such 4D simulation is shown in Figure 7, which illustrates a virtual surveying sequence of the building structure arising from the information included in the BIM model (involving parametric definition of element category, base level, horizontal 4D and vertical 4D) as well as in the task planning software package (tasks sequence involving starting/concluding dates and interconnections among them).

Note elements in grey represent those which are expected to have been concluded at the particular instant of the execution snapshot, whereas elements in green stand for those for which execution is supposed to be in progress. Of course, elements whose execution had not yet been started would be non-visible. For the particular case in Figure 7, for instance, both foundation floors (-1 and -2), as well as part of floor 1, had already been completed; moreover, four pillars in floor 1 are represented to be in progress.

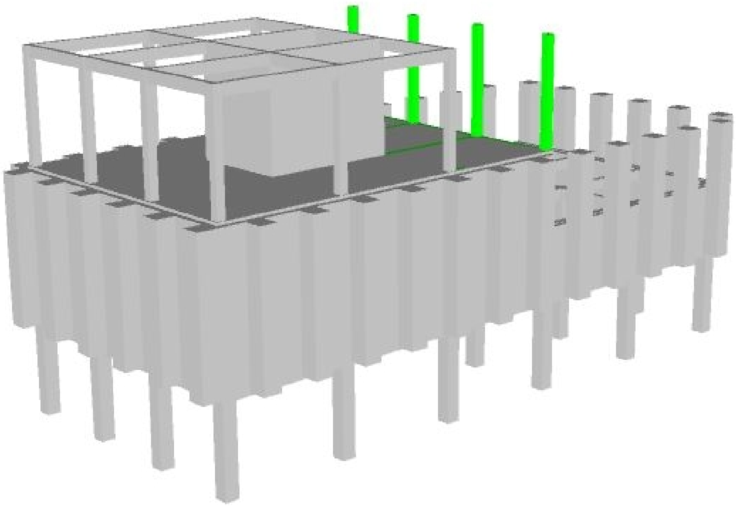

FIG. 7. 4D project simulation.

Figure 8 illustrates a temporal delay in the execution stage, so that a general horizontal displacement as related to the red time-reference line is accomplished. Such time delay is accounted for in the planning software at an initial stage. Finally, a couple of joint snapshots of the structure survey according to the abovementioned colour code are shown in Figure 9. Elements in grey are those which had already been completed, whereas those in green are the elements which had not been completed yet -but indeed should had if no delay had been achieved-. This way, the visualization of potential execution delays at any instant, and moreover the consequences on the remaining tasks, are ensured.

Foundation	**12 days**	**100%**	**Fri 10/06/16**	**Mon 27/06/16**
C_foun_v1	2 days	100%	Fri 10/06/16	Mon 13/06/16
C_foun_v2	2 days	100%	Tue 14/06/16	Wed 15/06/16
C_foun_v3	2 days	100%	Thu 16/06/16	Fri 17/06/16
C_foun_v4	2 days	100%	Mon 20/06/16	Tue 21/06/16
C_foun_v5	2 days	100%	Wed 22/06/16	Thu 23/06/16
C_foun_v6	2 days	100%	Fri 24/06/16	Mon 27/06/16
Level -2	**12.75 days**	**100%**	**Tue 28/06/16**	**Thu 14/07/16**
Level -1	**26 days**	**100%**	**Wed 29/06/16**	**Thu 04/08/16**
Level 1	**77.25 days**	**100%**	**Fri 15/07/16**	**Tue 01/11/16**
Level 2	**28.75 days**	**100%**	**Tue 19/07/16**	**Mon 29/08/16**
Level 3	**27 days**	**100%**	**Wed 10/08/16**	**Fri 16/09/16**
Level 4	**27 days**	**100%**	**Tue 30/08/16**	**Thu 06/10/16**
Level 5	**18 days**	**100%**	**Tue 20/09/16**	**Thu 13/10/16**
Terrain and Excavations	**162.5 days**	**100%**	**Mon 18/04/16**	**Wed 30/11/16**
Shoring	11 days	100%	Mon 18/04/16	Mon 02/05/16
Terrain	0.75 days	100%	Tue 29/11/16	Wed 30/11/16
Door of lifts	**35 days**	**100%**	**Wed 12/10/16**	**Wed 30/11/16**
Courtain Walls and Partitions	**35 days**	**100%**	**Tue 11/10/16**	**Tue 29/11/16**

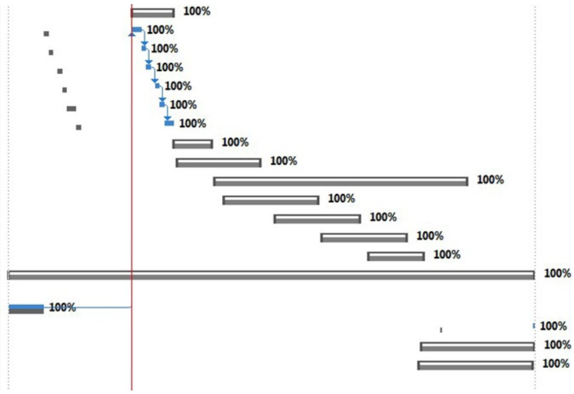

FIG. 8. Actual task-status update in temporal planning.

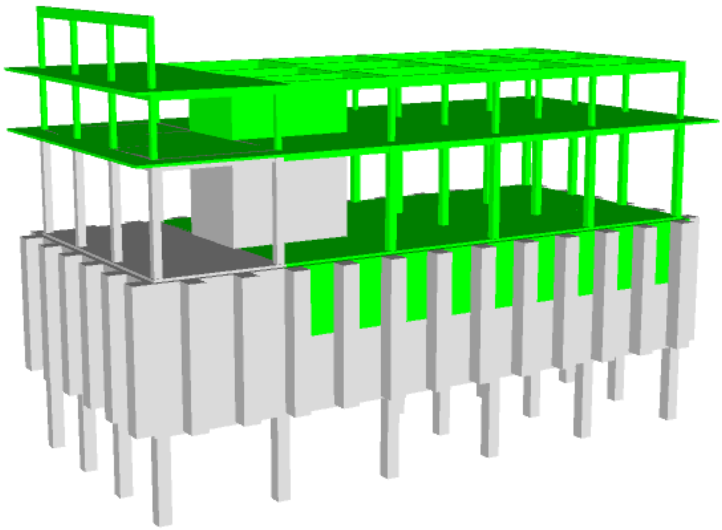

FIG. 9. Planned 4D simulation *vs* actual 4D simulation.

In sum, the structure's planning phase allowed a detailed virtual visualization of the execution progress based on the input featuring parameters of the BIM model and of the time planning software. Subsequently, a 4D simulation to set a comparison between the planning phase and the actual construction phase was carried out so that deviations between the planned and the actual tasks were straightforwardly identified.

Table 1 accounts for a comparison between traditional planning and 4D simulation through a variable-based assessment. For this specific purpose, the person in charge of each company involved in the present study completed the information of columns *Conventional, 4D* and *Weighting* (variables) for each of the factors in the first column, always accounting for the following concerns:

- *Conventional* and *4D* columns: numerical value ranging from 1 (*unsatisfactory*) to 5 (*optimal*).
- *Weighting* column: percentage parametrizing relevance of the particular factor as compared to the remaining ones.

Values from the 33 companies were averaged as listed below. Traditional planning in project execution (rated 3.10) was seen to be less efficient than 4D simulation (rated 4.00). However, conventional planning was less time-consuming than 4D simulation (rated 4 out of 5 as compared to 3 out of 5, respectively), whereas 4D simulation was significantly more effective than traditional planning in terms of progress' visual monitoring and change management (rated 4 as compared to 2, respectively).

Variable	Conventional	4D	Weighting	Weighted Conventional	Weighted 4D
Execution time	4	3	10%	0.40	0.30
Planning difficulty	3	4	5%	0.15	0.20
Information viewing	2	4	10%	0.20	0.40
Documentation use ease in the office	4	4	5%	0.20	0.20
Documentation use ease in field	4	3	10%	0.40	0.30
Understanding documentation	3	4	5%	0.15	0.20
Information quantity and organization	3	5	10%	0.30	0. 50
Change management and control	2	4	10%	0.20	0.40

Possibility of optimizing work performance	3	4	10%	0.30	0.40
Extraction of planning reports and ratios	4	2	5%	0.20	0.10
Updating ease	3	5	20%	0.60	1.00
TOTALS	35	43	100%	3.10	4.00

Table 1. Comparison between traditional planning and 4D simulation.

On another note, the simple data updating allowed by 4D simulation was an interesting point, as all the BIM information depends on parameters values. Information updating was therefore based on editing these parameter values.

4. DISCUSSION

The Standish Group 2015 Chaos Report surveyed around 50,000 projects worldwide between 2011 and 2015 (*Hastie et al.,* 2015). The authors regarded as *successful* any project which met the planned time and budget, and accordingly reported the concluding data listed in Table 2. As it can be seen, the rate of projects that were delayed and exceeded the expected cost approached 50%. In this sense, 4D simulation definitely provide a valuable graphical tool not only for architects and engineers but also for contractors, subcontractors and suppliers.

	2011	2012	2013	2014	2015
Successful	29%	27%	31%	28%	29%
Challenged	49%	56%	50%	55%	52%
Failed	22%	17%	19%	17%	19%

Table 2. Quantification of *successful*, *challenged* and *failed* projects along the period 2011-2015 according to criteria reported by *Hastie et al.* 2015.

Also, project simulations would therefore ensure a better monitoring and understanding to stakeholders. In addition, if any disagreement from a project agent about duration or interdependences of activities is accounted for, 4D simulation might certainly serve to other stakeholders to make a clear decision on any particular issue.

Time planning is an activity which shows inherent difficulties and therefore lacks easy handling, provided it involves potential changing scenarios. However, planning tools can be used by stakeholders as a sort of information centre to account for their knowledge and experience. As an overall purpose, 4D simulation is aimed at achieving an accurate time planning, thus providing the client with reliable information on the actual duration and costs of a given project. The key advantage of planning programs lies in their ability to simultaneously manage a large number of tasks linked to time slots as well as to ensure appropriate scheduling update, thus ensuring accurate monitoring of the project progress.

Visual building planning through the implementation of task sequencing can help contractors and subcontractors understand the degree of completion of the project, and hence clarify the scope of the involved tasks. In sum, this graphical tool is intended to make information more intuitive and therefore to supplement some other widely accepted and more powerful planning methodologies like for instance PERT, CPM, ROY, *Precedences*, *Tense Flow*, *Links*, etc.

5. CONCLUSIONS

The 4D simulation procedure reported along the present manuscript has proved to increase the efficiency in the planning process of construction projects. The average ratings achieved for the various involved items were computed as 3.1 and 4.1 for the temporal planning and the

4D simulation, respectively –as referred to a score interval ranging from 1, *unsatisfactory*, up to 5, *optimal*-.

Traditional planning was observed to be less time-consuming –as much as 20%- than the 4D simulation method (rated 4 out of 5 as compared to 3 out of 5, respectively). However, the 4D simulation was seen to be significantly more effective than traditional planning in terms of progress' visual monitoring and control (rated 4 as compared to 2, respectively); in particular, 4D simulation improvement in terms of visual control was quantified as 40% higher as compared to conventional planning.

On another note, virtual visualization of the building execution phase in the 4D simulation definitely helped improve the understanding of the construction process. Such degree of clarification was quantified as 20% higher than for the case of conventional planning, which would definitely provide stakeholders with a better understanding on the construction progress and would therefore help them make appropriate decisions at an earlier stage (hence with no drastic implications on forthcoming stages of the project).

With regard to the ease for information updating, 4D simulation were observed to be 40% more efficient than conventional planning, which is justified by the fact that updating in 4D simulation involves a mere change in the values of the parameters implemented in the BIM model or in the planning software.

As a final point, it should be noted that the larger the project, the less efficient manual planning becomes since the involved information would not entirely be under control. However, the application of BIM technology to task planning is definitely an appropriate choice for the sake of clarity, organization and ease of handling of the execution scheduling.

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