MANAGEMENT OF BUILDING SUPPORTED ON VIRTUAL INTERACTIVE MODELS: CONSTRUCTION PLANNING AND PREVENTIVE MAINTENANCE

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SUMMARY: Virtual Reality (VR) models were created in order to help in the maintenance of exterior closures and interior finishes of walls and in the construction of buildings. The maintenance model allows the visual and interactive transmission of information related to the physical behaviour of the elements. To this end, the basic knowledge of material most often used in walls, anomaly surveillance, techniques of rehabilitation, and inspection planning were studied. This information was included in a data base that supports the periodic inspection needed in a program of preventive maintenance. The results are obtained interactively and visualized in the virtual environment itself. A second prototype based on VR technology with application to construction planning, was implemented. This model intends to present the project in a three-dimensional (3D) way, connected to construction planning schedule, resulting in a valuable asset in monitoring the development of the construction activity, based on the construction planning designed. The 4D application considers the time factor showing the 3D geometry of the distinct steps of the construction activity, according to the plan establish to the construction. The VR technology is used, and presented as an innovative visual tool in supporting the fields of construction planning and of maintenance of buildings. It helps to establish a collaborative network between partners in a building.

KEYWORDS: Virtual Reality, Maintenance, Construction, Interaction, Collaboration.

1. INTRODUCTION

The main aim of a research project, now in progress at the Department of Civil Engineering of the Technical University of Lisbon, is to develop virtual models as tools to support decision-making in the planning of construction management and maintenance. A first prototype concerning the lighting system has already been completed (Sampaio et al, 2009). A second prototype concerning the maintenance of the closure of walls, both interior walls and façades, was also developed (Gomes, 2010). Another prototype was developed supported on Virtual Reality (VR) technology, where the construction of a building and the related sequence of activities are used (Santos, 2010).

The interactive models integrate Virtual Reality (VR) technology and an application implemented in Visual Basic (VB) language. The maintenance model allows interaction with the three-dimensional (3D) geometric model of a building, visualizing components for each construction. It is linked to a database of the corresponding technical information concerned with the maintenance of the materials used as exterior closures and interior finishes. The principal objective of the interactive VR prototype is to support decision-making in the maintenance domain.

The present project aims to bring important contributions to this domain, through the implementation of virtual models able to relating the behaviour of materials, their characteristics, anomalies and repair work to each other. During this work the basic knowledge of the topics involved, such as aspects related to the materials, the techniques of rehabilitation and conservation and the planning of maintenance is outlined and discussed in addition, methods of interconnecting this knowledge with the virtual model are explored.

In construction management, technical drawings have had, throughout times, a crucial role in communication between the numerous partners in a project. Generally, drawings represent formal solutions, and often incompatibility mistakes are only detected in advance stadium, on site, with additional costs (Webb and Haupt, 2003). In this field, 4D models, where the time factor is added to the 3D model, promote the interaction between the geometric model and the construction activity planning, allowing immediate perception of the work evolution. Moreover, VR technology makes possible the interaction and the visualization of the construction work evolution.

The prototypes were trialled in concrete projects. The walls in a building have a continuous lifestyle, so they requires the study of preventive maintenance (the planning of periodical local inspections) and of corrective maintenance with repair activity analysis. The wall model facilitates the visual and interactive access to results, supporting the definition of inspection reports. It is possible to apply this to other building situations whether in new constructions or those needing rehabilitation. In the construction model the construction planning used is also realistic and considers the designed and written documentation, measurements and quantities map, specifications and regulations with relevance to the project.

2. INTERACTIVE AND COLLABORATIVE MODELS

Virtual Reality technology can support the management of data that is normally generated and transformed or replaced throughout the lifecycle of a building, beginning in its construction. This technology becomes an important support in the management of buildings allowing interaction and data visualization. At present, the management of building planning can be presented in a 3D form and various materials can be assigned to the fixtures and furnishing enabling the user to be placed in the virtual building and view it from inside as well as outside. This study contemplates the incorporation of the 4th dimension, that is, time, into the concept of visualization. The focus of the work is on travelling through time: the ability to view a product or its components at different points in time throughout their life. It is envisaged that the incorporation of the time dimension into 3D visualization will enable the designer/user to make more objective decisions about the choice of the constituent components of the building. In maintenance the time variable is related to the progressive deterioration of the materials throughout the building's lifecycle and with the construction planning it self.

In construction industry, from the conception to the actual implementation, project designs are presented mostly on paper, even though the two dimensional reading is often not enough, as mistakes can be introduced in early stages of conception or elements misunderstood on the construction site. 3D models present an alternative to avoid inaccuracies, as all the information can be included with the necessary detail (Grilo et al, 2001). Computer systems used in construction for graphic representation have experienced a vast evolution, allowing new ways of

creating and presenting projects. 4D models, also labelled as 3D evolutionary models, permit a better comprehension of the project throughout its life, minimizing the information loss through the chain of events. In addition VR technology can present a step-by-step guide in assembling complex structures in an interactive way. One of the benefits of VR in construction is the possibility of a virtual scenario being visited by the different specialists, exchanging ideas and correcting mistakes. Some applications are already offering the possibility of communication between different specialties while developing a mutual project (Yerrapathruni et al, 2003).

3. THE INTERIOR WALLS VR MODEL

The maintenance of walls prototype incorporates interactive techniques and input devices to perform visual exploration tasks. To support this system a data base was created which included a bibliographic research support made in regard to the closure materials used in the exterior walls of a building, anomalies concerning different kinds of covering material, and corrective maintenance. Repair activities were also studied. The programming skills of those involved in the project had to be enhanced so that they could achieve the integration of the different kinds of data bases needed in the creation of the interactive model.

The 3D model linked to a data base concerning maintenance produces a collaborative virtual environment, that is, one that can be manipulated by partners interested in creating, transforming and analyzing data in order to obtain results and to make decisions. For example, inspection reports can be defined and consulted by different collaborators. The process of developing the prototype interface considers these purposes. The developed prototype associates the characteristics of the coating component of the exterior and interior walls to activities concerning the maintenance of buildings (Fig. 1).
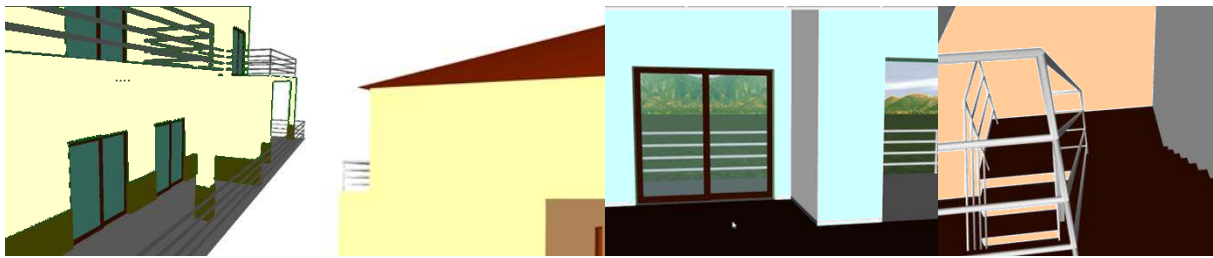

FIG 1: 3D model of the house: coating elements of exterior and interior walls.

Façade coatings play an important role in the durability of buildings, since they constitute the exterior layer that ensures the protection of the wall against the aggressive actions of physical, chemical or biological nature. Naturally, they should also give the façade the required decorative effect. Since this building component is exposed to bad atmospheric conditions it frequently shows an evident degree of deterioration, requiring maintenance interventions. To perform maintenance activities a survey of failures in the building must be conducted in order to arrive at the best solution for repair and maintenance.

3.1 Characteristics of the materials used in façades

In order to better understand the operation of façade coating, bibliographic research of materials usually applied to façade coatings was carried out and a table of characteristics of these was drawn up. Subsequently, a survey was made of anomalies, probable causes, solutions and methods of repair for each of the coatings studied (Fig. 2). The visualization of the maintenance data of a building and the impact of time on the performance of these exterior closure materials require an understanding of their characteristics (Gomes and Pinto, 2009):

- *Types of material*: painted surfaces, natural stone panels and ceramic wall tiles;
- *Application processes*: stones (panel, support devices, adherent products, …); ceramic tiles (fixing mechanism, procedures, …); painted surfaces (types of paint products, prime and paint scheme surface, exterior emulsion paints, application processes);
- *Anomalies*: dust and dirt, lasting lotus leaf effect, covering power, insufficient resistance to air permeability or weatherproof isolation, damaged stones or ceramic tiles, alkali and smear effect, efflorescence, fractures and fissures ….;

- *Repair works*: surface cleaning, wire truss reinforcing, cleaning and pointing of stonework joints, removing and replacement of ceramic wall tiles, removing damaged paint and paint surface, preparing and refinishing stone panels, ...

FIG 2: Different type of materials applied as façade coatings presenting anomalies.

Depending on the role that the façade coatings play on the wall as a whole they can be classified as finishing, sealing or thermal insulation. The most frequent materials used as coating finishes are painting, tiling and, as sealing coating of the natural stone:

- *Paint coating* contributes to the aesthetic quality of the building and its environment and also protects the surface of the exterior wall against corrosion, deterioration and penetration of aggressive agents (Lopes, 2008). In order to obtain a good performance as an exterior coating, several aspects must be considered, such as covering power and resistance to water, sunlight, chemical products and to the development of micro organisms;

- The *ceramic coating* consists essentially of tiling panels, cement and adhesive and the joints between the slabs. The application of ceramic tiling to building façades has considerable advantages particularly as some degree of waterproofing is afforded by the glazed surface along with a great resistance to acids, alkalis and vapour. Other advantages are that it does not need painting and that it can be easily applied or substituted during repair work (Ferreira et al, 2009);

- The use of *natural stone* in the coating of façade surfaces is a good solution both technically and aesthetically. The principal characteristics of the stones are: reduced water absorption, sufficient mechanical resistance to bending and impact, abrasion and shearing parallel to the face of the slabs (Veiga and Malanho, 2009).

3.2 The database

The most frequent anomalies that occur in the coated façades were analysed in order to create a data base linked to the virtual model that could support planning of inspections and maintenance strategies in buildings. The database contains the identification of anomalies that can be found in each type of material used in façades and the corresponding probable cause. For each kind of anomaly the most adequate repair solutions are also selected and included in the data base. The following example concerning deficiencies in tiles presents the methodology implemented in this virtual application (Table 1).

TABLE 1: Example of anomalies and the associated repair solution.

Anomaly	Specification of the anomaly	Repair solution	Repair methodology
Detachment			1º Removal of the tiles by cutting grinder with the aid of a hammer and chisel;
	Fall in areas with deterioration of support	Replacement of the coat (with use of a repair stand as necessary)	2º Timely repair of the support in areas where the detachment includes material constituent with it; 3º Digitizing layer of settlement; 4º Re-settlement layer and the tiles.

Cracking / Fracturing			1º Removal of the tiles by cutting grinder;
			2º Removal of material adjustment in the environment and along the joint;
	Failure of the support (wide cracks with well defined orientation)	Replacement of the coat (with repair of cracks in the support)	3º Repair of cracks, clogging with adhesive material (mastic);
			4º Settlement layer made with cement in two layers interspersed with glass fibre;
			5º Re-settlement layer and the tiles.

The characteristics related to anomalies, causes, repair solutions and rehabilitation tasks were included in a database of each type of material and linked to the 3D model of the building. Thus, the virtual model gives users the ability to transmit, visually and interactively, information related to the closure properties of exterior walls, allows them to analyse the anomalies observed in an inspection of the real building and to predict the corresponding repair work. The 3D virtual model can be seen, therefore, as an important tool for anomaly surveillance in structures and for supporting decision-making based on the visual analysis of alternative repair solutions

3.3 The interface

The implementation of the prototype system makes use of graphical software programming, *Visual Basic 6.0 Microsoft*, software to establish an adequate database, *Microsoft office access,* graphical drawing system, *AutoCAD Autodesk* and VR technology based software, *EON Studio* (EON, 2010).

Human perceptual and cognitive capabilities were taken into account when designing this visualization tool so the model is easy to use and does not require sophisticated computer skills: many potential users are not computer experts. It uses an interactive 3D visualization system based on the selection of elements directly within the virtual 3D world. Furthermore, associated with each component, there are integrated databases, allowing the consultation of the required data at any point in time. The interface is composed of a display window allowing users to interact with the virtual model, and a set of buttons for inputting data and displaying results (Fig. 3).
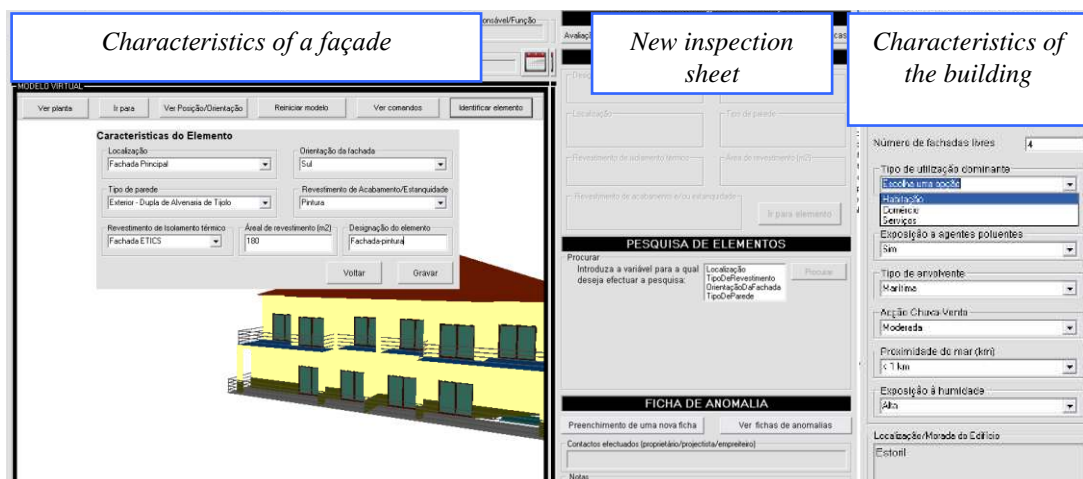

FIG 3: The main interface of the interactive application.

For each new building to be monitored the characteristics of the environment (exposure to rain and sea) and the identification of each element of the façades must be defined. The data associated to each element are the building orientation, the type of exterior wall (double or single), and the area and type of coating. Once each monitored element has been characterized, several inspection reports can be defined and recorded and thereafter consulted when needed. An inspection sheet is accessed by the main interface (Fig. 4).

Using the drop-down menus allowed by the interface, the user can associate the characteristics of the observed anomaly to: a façade element; the type of anomaly, the specification, details and the probable cause of the anomaly, an adequate repair solution and pictures taken in the building. After completing all fields relating to an anomaly, the user can present the report as a *pdf* file.

3.4 The case study

First, the 3D geometric model of a building case was created. The building consists of a ground-floor, a 1st floor and an attic. The coating elements of the walls were then modelled as independent geometric objects (Fig. 5). In this way, each element can then support characterization data of the applied material and different kinds of information related to maintenance.

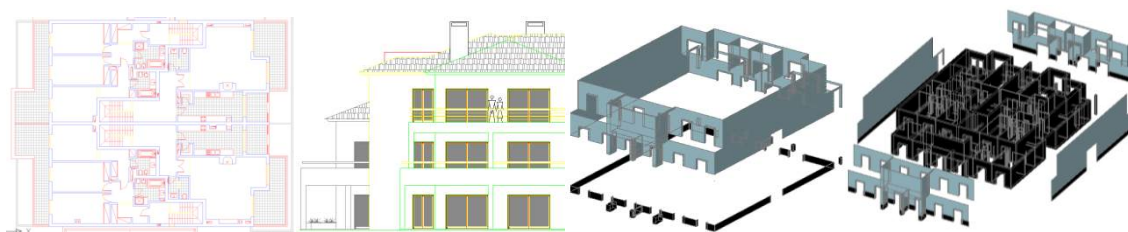*FIG 4: Selecting data in the inspection interface.*

FIG 5: Steps of the geometric modelling process.

All coatings studied were considered in this case-study. Thus it was assumed that the main façade is covered with tile and the remaining façades are painted while hall façades are of natural stone. Fig. 6 shows how to identify a façade in the virtual model of the building. The Fig. 7 includes the inspection report of the anomaly considered in Table 1.
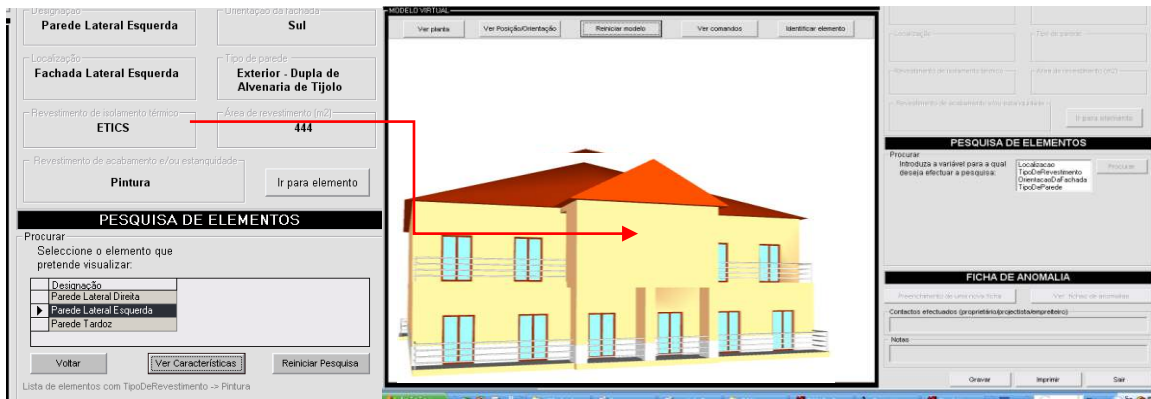
FIG 6: Identification of a façade element.

FIG 7: Inspection sheet report.

4. THE INTERIOR WALLS MAINTENANCE VR MODEL

An identical analysis of the characteristics, anomalies and repair works concerning the interior finish materials was carried out (Sampaio et al, 2010). With this information a data base was created. Another inspection interface was defined for the painted surfaces of interior walls, also associated to repair solutions and corresponding methodologies of rehabilitation (Fig. 8).
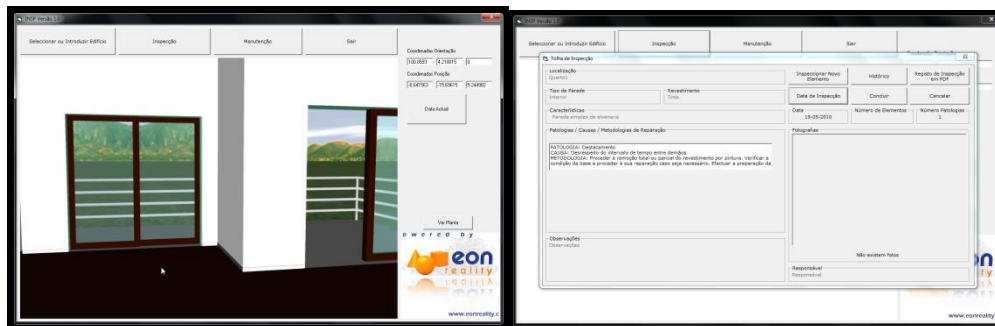

FIG 8: Painted coating of interior walls of the building and the inspection interface.

In addition the model identifies the period of time between the application of new paint and the predicted time when the next paint will be needed. The colour changes between white (new) and red (when an area needs to be painted again, Fig. 9).

FIG 9: Changing colors related to the maintenance of the painted interior wall.

The data of periodic on-site inspections included in preventive maintenance is taken into account for each monitored element of the interior wall (Fig. 10). Thus, when the date of interaction with the prototype is compared with the date predicted for the new paint application, the correspondent RGB (red, green and blue) values are calculated. Different RGB values generate different colour, using this virtual model. Therefore, by using data visualization supported by this VR technology, it is possible to estimate if the wall needs painting immediately or not.
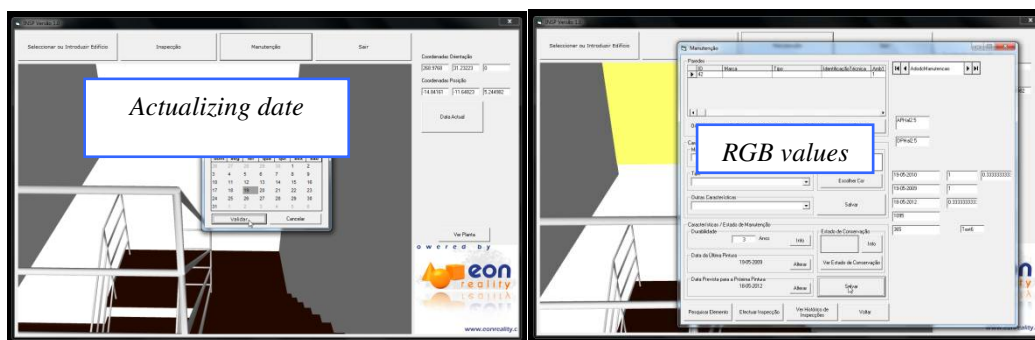
FIG 10: Changing date of interaction and the correspondent RGB values.

5. THE CONSTRUCTION VR MODEL

Construction management can be defined as *the planning, co-ordination and control of a project from conception to completion (including commissioning) on behalf of a client requiring the identification of the client's objectives in terms of utility, function, quality, time and cost, and the establishment of relationships between resources, integrating, monitoring and controlling the contributors to the project and their output, and evaluating and selecting alternatives in pursuit of the client's satisfaction with the project outcome* (Walker, 2002).

Therefore, it is essential the project designer comprise the knowledge to correctly identify the different stages of the construction planning, as well as take into consideration the logistics and resources involved in the project. The construction management and its planning depends on the target, while the people in the construction site have the need for a more detailed presentation, the client may want something more general and wide-ranging. Hadju (1997), in *Network Scheduling for Construction Project Management*, define the steps to create a good planning:

- Task *definition* and *description*, considering the detail required;
- Task *interdependencies* definition and creation of a list of predecessors and successors;
- *Network design*, considering tasks' interdependencies;
- *Resources* and *time* estimation;
- *Base calculations*, including total project length;
- *Advanced calculations*, aiming a more efficient project, considering, cost, resources and task duration;
- *Project control* throughout its implementation;

- *Project revision*, considering the tasks, their duration and the necessary resources, with the intention of presenting alternatives to the established planning.

The steps one through five comprise the initial stage, six and seven consist of the scheduling stage, and the last is the project stage. There are several different factors to consider in the process of planning: Work scope; time; resources; costs; quality; communication; risk; contracts and procurement.

When going through the other factors, the stress is, most of the times, put on the triangle time-resources-costs (Casimiro, 2006). These three factors are interconnected and interdependent. Time has a great significance in planning, as the tasks' length must converge to a project duration compatible with the deadline. In defining the duration of a task the available resources must be considered. And this availability is intrinsically connected to the costs associated with the project.

On the present work, a prototype was developed supported on VR technology, where the construction of a building and the related sequence of activities are used. Virtual Reality technology is often considered a way to simulate reality through graphics projection, allowing the user to interact with their surroundings. The construction planning used in the implemented prototype is realistic and considers the designed and written documentation, measurements and quantities map, specifications and regulations with relevance to the project.

A prototype concerning the management of the construction activity was created with the purpose to present a 3D model integrated with its construction planning schedule (Santos, 2010). The application was developed in three stages: the planning, the modelling, and the integration of the first two stages:

- The *planning* has to consider the final purpose of the presentation, and the definition of the tasks and its detail has to be done according to this idea. Using *Microsoft Project*, the tasks are introduced and the relations between them defined;

- The *geometric modelling* needs to relate correctly with the tasks defined in the planning stage. Using *AutoCAD* the layers do the distinction between the different tasks and the elements are creating considering the detail necessary to the correct comprehension. The application also presents a real-time illustration of the construction evolution through *photographs* from the site, taken at specific points in time;

- The third stage, the *integration*, makes use of two programs: *EON Studio* and *Microsoft Visual*, where the first takes the 3D model created with *AutoCAD* and introduces it in the application developed using the second.

The developed application integrates all the components described with the interface presented in Fig. 11. The application has the following organization: Virtual model (1); Pictures of construction site (2); Planning task list (3); and Gantt map (4).
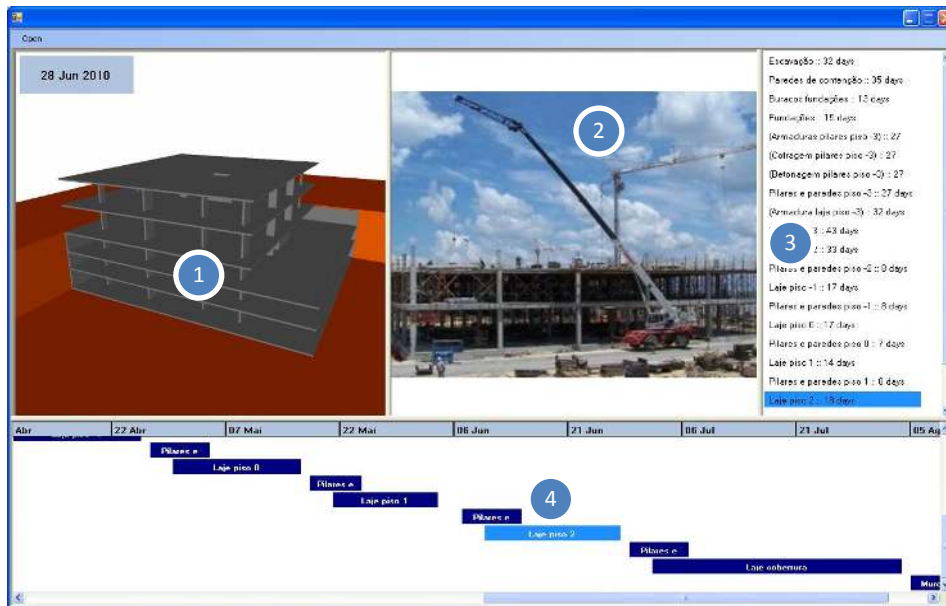
FIG 11: Application interface.

The interaction with the application is made through windows 3 and 4. Both, the task list items and Gantt map bars, are buttons that when pressed send the information to the *EON* about the task selected, and in return *EON* presents the model in the current state. This meaning that it shows and hides specific elements considering the construction's current stage. In this prototype only the state of elements and position of camera is changed.

Any new objects can be introduced in the application, just by modelling the new elements considering their position relatively to the ones already in the simulation and programming the associated action in *EON Studio*. Likewise, the application accepts any kind of construction project, as long as the imperatives of their implementation are met. Additionally, and with the appropriate models, it can also be used in construction site management. *EON Studio* also offers the possibility to change the material associated with each element, creating a more realistic model.

This prototype's weakness is the time needed to make the preparation for the actual interaction with the application. Modelling a building may not be much extended. However, the programming of the actions in *EON Studio* can be time-consuming.

5.1 The case study

As a method of testing the application, a construction project was implemented. Particularly the structure of a building, using its graphic documentation, such as architectural and structural blueprints, the project description and construction planning was defined. The whole project was simplified to meet this paper's academic purposes, and the list of tasks was defined considering the more characteristic stages in a construction process, and also a few tasks focused in construction details of certain elements (Fig. 12). As a result, *AutoCAD* layers were created for each task defined and the 3D model assembled.

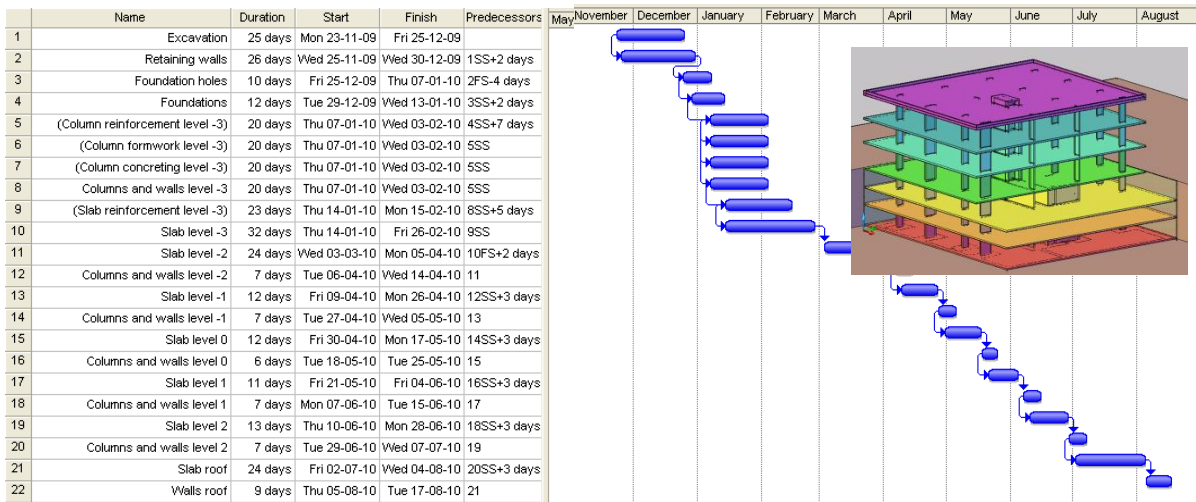|		Name	Duration	Start	Finish	Predecessors
1		Excavation	25 days	Mon 23-11-09	Fri 25-12-09	
2		Retaining walls	26 days	Wed 25-11-09	Wed 30-12-09	1SS+2 days
3		Foundation holes	10 days	Fri 25-12-09	Thu 07-01-10	2FS-4 days
4		Foundations	12 days	Tue 29-12-09	Wed 13-01-10	3SS+2 days
5		(Column reinforcement level -3)	20 days	Thu 07-01-10	Wed 03-02-10	4SS+7 days
6		(Column formwork level -3)	20 days	Thu 07-01-10	Wed 03-02-10	5SS
7		(Column concreting level -3)	20 days	Thu 07-01-10	Wed 03-02-10	5SS
8		Columns and walls level -3	20 days	Thu 07-01-10	Wed 03-02-10	5SS
9		(Slab reinforcement level -3)	23 days	Thu 14-01-10	Mon 15-02-10	8SS+5 days
10		Slab level -3	32 days	Thu 14-01-10	Fri 26-02-10	9SS
11		Slab level -2	24 days	Wed 03-03-10	Mon 05-04-10	10FS+2 days
12		Columns and walls level -2	7 days	Tue 06-04-10	Wed 14-04-10	11
13		Slab level -1	12 days	Fri 09-04-10	Mon 26-04-10	12SS+3 days
14		Columns and walls level -1	7 days	Tue 27-04-10	Wed 05-05-10	13
15		Slab level 0	12 days	Fri 30-04-10	Mon 17-05-10	14SS+3 days
16		Columns and walls level 0	6 days	Tue 18-05-10	Tue 25-05-10	15
17		Slab level 1	11 days	Fri 21-05-10	Fri 04-06-10	16SS+3 days
18		Columns and walls level 1	7 days	Mon 07-06-10	Tue 15-06-10	17
19		Slab level 2	13 days	Thu 10-06-10	Mon 28-06-10	18SS+3 days
20		Columns and walls level 2	7 days	Tue 29-06-10	Wed 07-07-10	19
21		Slab roof	24 days	Fri 02-07-10	Wed 04-08-10	20SS+3 days
22		Walls roof	9 days	Thu 05-08-10	Tue 17-08-10	21

FIG 12: Construction planning, the Gantt map and the 3D model of the building structure.

Using the *EON system*, the task list and the virtual model are connected. When selecting a task, the relevant construction stage is presented. Details of the construction work are presented in Fig. 13. The date concerning each visualized task is shown in the upper left corner of the virtual model window.
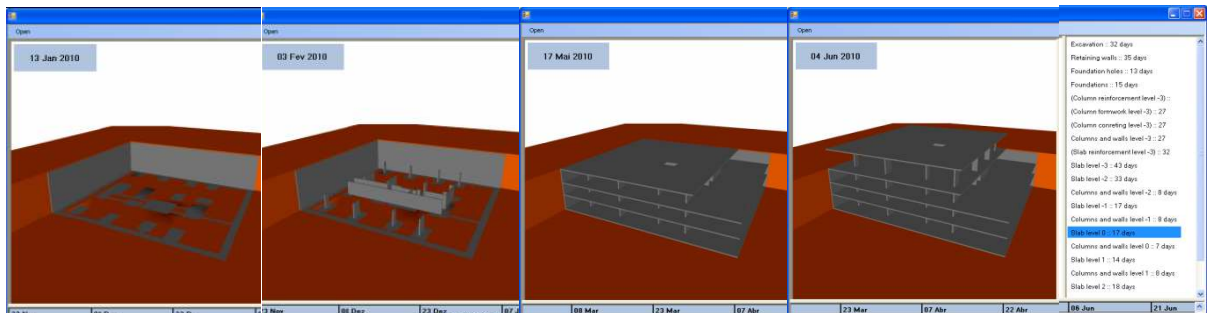

FIG 13: Application's virtual model and task list in a sequence of the construction process.

When a task is selected in the construction planning chart a static position of the model is presented. A first view is always linked to a task. This was established to provide an easier interaction with the 3D model, and to focus the attention of the user on the important sections on each task, guiding them correctly through the development of the construction. Next, in order to obtain the same point of view of the photo, the user can manipulate the virtual model, choosing an identical perspective. So, visualizing what is planned and what was done in the real place, the construction work is better compared and analyzed (Fig. 14). In addition the user can manipulate the model walking through the virtual building observing any construction detail he wants to compare.
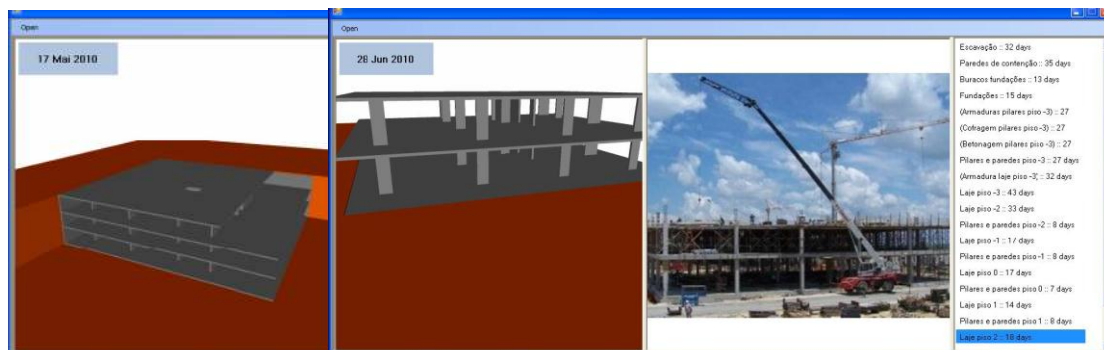
FIG 14: Rotation applied to the virtual model.

In this example, some construction details were modelled, including one column progress. This progress is presented in Fig. 15, throughout three stages. A detail of the reinforcement and the concentration of a slab are also presented in figure.
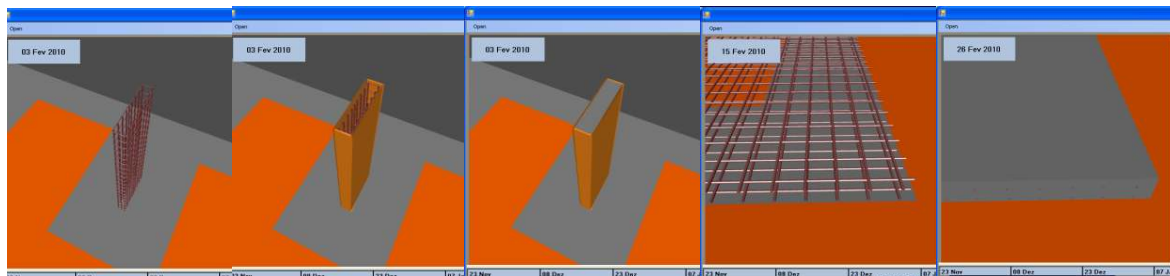

FIG 15: Column and slab construction progress: reinforcement, formwork and concreting.

When constructing a building, the planning sometimes needs to be changed due to unexpected contingencies. Implementing these changes in the prototype is actually very simple, as the user just have got to change the tasks new start and finish dates in *MS Project* and load the new file into the application.

6. CONCLUSIONS

Virtual Reality technology and its capability of interaction and connectivity between elements were employed in the developed prototypes, within a research project, offering several benefits both in presenting and developing projects and in supporting decision-making in the maintenance domain.

A VR model to support the maintenance of walls enables the visual and interactive transmission of information related to the physical behaviour of the elements. The model shows the characteristics of each element of the building in the model and the information related to inspection, anomalies and repair works. As the 3D model is linked to a data base in an interactive environment and has a friendly interface to deal with this knowledge, it allows a collaborative system. With this application the user may fully interact with the program referring to the virtual model at any stage of the maintenance process and analyse the best solution for repair work. It can also support the planning of maintenance strategies. The developed software is easy to handle and transport for on-site inspections and comprises information of the causes, solutions and methods for repairing.

Technical drawings and explanatory texts often have little detail and are frequently insufficient in fully comprehending the object. Mistakes can easily be caught before construction a start, which translates in time and cost reduction. The construction planning model can be used with any kind of construction project and, being a flexible application, accepts new data when necessary, allowing for a comparison between the planned and the constructed. The prototype can also be expanded to include other aspects of construction management, such as resource administration, or to have a real-time access to the construction, through the use of cameras installed on site. The use of new mobile technologies could move the application to the construction site, clarifying any doubts about location or position of each component.

7. ACKNOWLEDGMENTS

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