

Virtual Environment in Civil Engineering

Construction and Maintenance of Buildings

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Abstract— This paper describes two prototype applications based on Virtual Reality (VR) technology for use in construction and maintenance planning of buildings. The first, applied to construction, is an interactive virtual model designed to present plans three-dimensionally (3D), connecting them to construction planning schedules, resulting in a valuable asset to the monitoring of the development of construction activity. The 4D application considers the time factor showing the 3D geometry of the different steps of the construction activity, according to the plan established for the construction. The 4D model offers a detailed analysis of the construction project. It allows the visualization of different stages of the construction and the interaction between all stakeholders during the actual construction activity. A second VR model was created in order to help in the maintenance of exterior closures of walls in a building. It allows the visual and interactive transmission of information related to the physical behavior of the elements. To this end, the basic knowledge of material most often used in faades, anomaly surveillance, techniques of rehabilitation, and inspection planning were studied. This information was included in a database that supports the periodic inspection needed in a program of preventive maintenance. This work brings an innovative contribution to the field of construction and maintenance supported by emergent technology.

Keywords- *Construction; Maintenance; Virtual reality; Interactive model.*

I. 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, PTDC/ ECM/67748/ 2006, "Virtual Reality technology applied as a support tool to the planning of construction maintenance". A first prototype for the lighting system had already been completed [1]. A second prototype concerning construction planning is now complete [2] and the VR model concerning maintenance of the closure of exterior walls is also finished [3]. This paper describes these two later models created as part of the overall research project.

These interactive models integrate Virtual Reality (VR) technology and applications implemented in Visual Basic (VB) language. The models allow interaction with the 3D geometric model of a building, visualizing components for each construction. They are linked to databases of the

corresponding technical information concerning construction planning and the maintenance of the materials used as exterior closures. The principal objective of the interactive VR prototypes is to support decision-making in the area of planning.

Information technology, namely 4D modeling (3D+time) and VR techniques is currently in use both in the construction activity and in education [4]. At the Department of Civil Engineering, some didactic models have already been generated. The research project presented in this paper follows on from that previous educational work: two 3D geometric models which support activity in the rehabilitation of buildings [5]; and three VR models developed to support classes in Civil Engineering (wall, bridge and roof construction) in Technical Drawing, Construction and Bridge disciplines [6]. The didactic VR models are in common use in both face-to-face classes and on an e-learning platform.

Virtual Reality technology can support the management of data that is normally generated and transformed or replaced throughout the lifecycle of a building. This technology constitutes an important support in the management of buildings allowing interaction and data visualization. At present, the management of building planning can be presented in 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, or the ability to view a product or its components at different points in time throughout their life. In maintenance, the time variable is related to the progressive deterioration of the materials throughout the building's lifecycle. It is implicit 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 construction management, over the years, technical drawings have played a crucial role in communication between the numerous partners in a project. Generally, drawings represent formal solutions, and often incompatibility mistakes are only detected at advanced stages, on site, accruing additional costs. In this field 4D models promote the interaction between the geometric model and construction activity planning, allowing immediate perception of the evolution of the work. In planning, in correct evaluation and the meeting of needs as they arise, 4D

models constitute a positive contribution to decision-making when establishing planning strategies [7].

Section II describes the maintenance model, highlighting the constitution of the database supporting the model, and the organization of a user-friendly interface designed to be used by an inspection worker. During the construction of this model, 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. This prototype was trialled in an actual project.

These aspects of the construction activity are in constant evolution, so require the study of preventive maintenance, through, for example, the planning of periodic local inspections and corrective maintenance with repair activity analysis. For this reason, the model facilitates the visual and interactive access to results, supporting the drawing-up of inspection reports.

The construction model, presented in Section III, brings an innovative aspect to 4D modelling as usually applied to construction planning, through the incorporation of pictures into the interface of the VR model, an important support element in the comparison between what is planned and what is in progress *in situ* after each construction task.

II. THE WALL MAINTENANCE MODEL

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 a physical, chemical or biological nature. Naturally, they should also give the façade the required decorative effect. Since this building component is exposed to adverse atmospheric conditions it frequently shows an evident degree of deterioration, requiring maintenance work. In order to arrive at the best solution for eventual maintenance and repair work, a survey of defects and deterioration must be conducted.

In order to better understand the operation of façade coating, bibliographic research of materials usually applied to this type of material 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. 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 [8] (Figure 1):

- Types of material: painted surfaces, natural stone panels and ceramic wall tiles;
- Application processes: stones (panel, support devices, adherent products, etc.); ceramic tiles (fixed 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 weather-proof isolation, damaged

stones or ceramic tiles, alkali and smear effect, efflorescence, fractures and fissures and so on;

- Repair work: 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, etc..



Figure 1: Different types of materials applied as façade coatings.

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 [9];
- 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 [10];
- 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.

A. The database

The most frequent anomalies that occur in the coated façades were analysed in order to create a database linked to the virtual model that could support the planning of inspections and maintenance strategies in buildings. This 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 type of anomaly the most adequate repair solutions were also selected and included in the database. The following example, concerning

deficiencies in tiles, illustrates the methodology implemented in this virtual application (Table 1).

TABLE I. EXAMPLE OF ANOMALIES AND THE ASSOCIATED REPAIR SOLUTION

Anomaly	<i>Detachment</i>	<i>Cracking / Fracturing</i>
		
Specification of the anomaly	Fall in areas with deterioration of support	Failure of the support (wide cracks with well defined orientation)
Repair solution	Replacement of the coat (with use of a repair stand as necessary)	Replacement of the coat (with repair of cracks in the support)
Repair methodology	<ol style="list-style-type: none"> 1. Removal of the tiles by cutting grinder with the aid of a hammer and chisel; 2. Timely repair of the support in areas where the detachment includes material constituent with it; 3. Digitizing layer of settlement; 4. Re-settlement of layer and tiles. 	<ol style="list-style-type: none"> 1. Removal of the tiles by cutting grinder; 2. Removal of material adjustment in the environment and along the joint; 3. Repair of cracks, clogging with adhesive material (mastic); 4. Settlement layer made with cement in two layers interspersed with glass fibre; 5. Re-settlement of layer and tiles

B. The interface

The implementation of the prototype system makes use of graphical software programming, *Microsoft Visual Basic 6.0*, software to establish a suitable database, *Microsoft office access*, graphical drawing system, *AutoCAD Autodesk* and VR technology based software, *EON Studio* [11].

Many potential users are not computer experts. Human perceptual and cognitive capabilities, therefore, were taken into account when designing this visualization tool with the result that the model is easy to use and does not require sophisticated computer skills. 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 (Figure 2). 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.

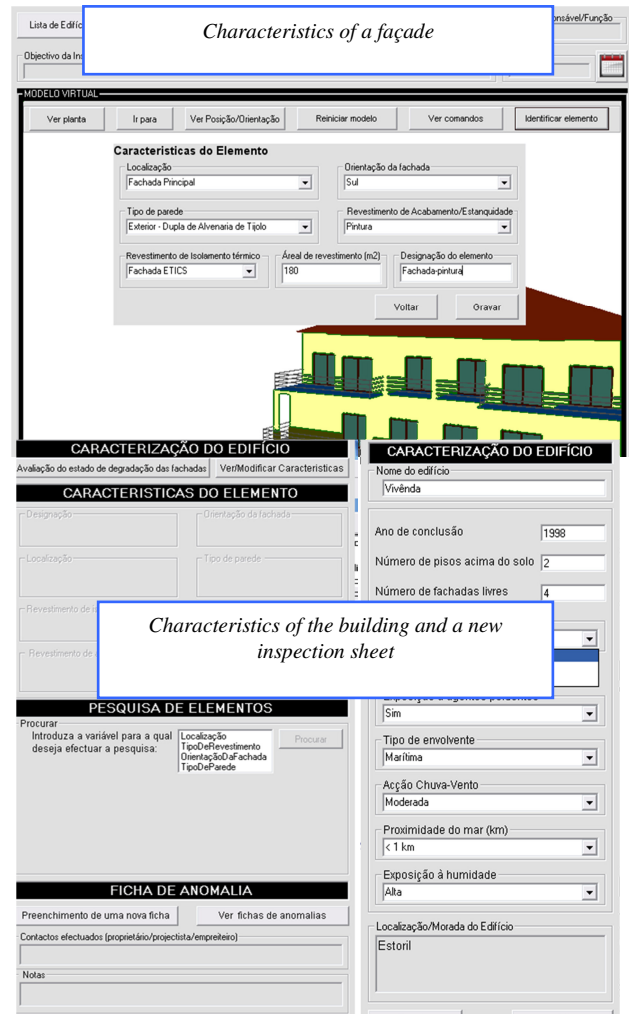


Figure 2: The main interface of the interactive application.

Once each monitored element has been characterized, various inspection reports can be defined and recorded and thereafter consulted when needed. An inspection sheet is accessed from the main interface (Figure 3).

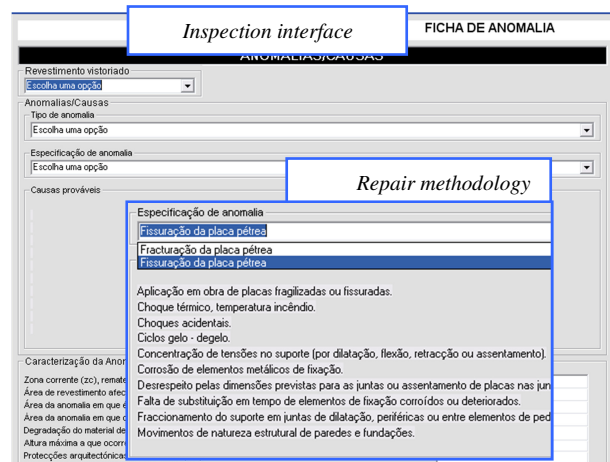


Figure 3: Inspection sheet interface

The inspection sheet includes the type of covering (natural stone, Figure 4), the anomalies (*Cracking /Fracturing*) and a list of possible causes to be selected and associated to the element. Several photos can be added.

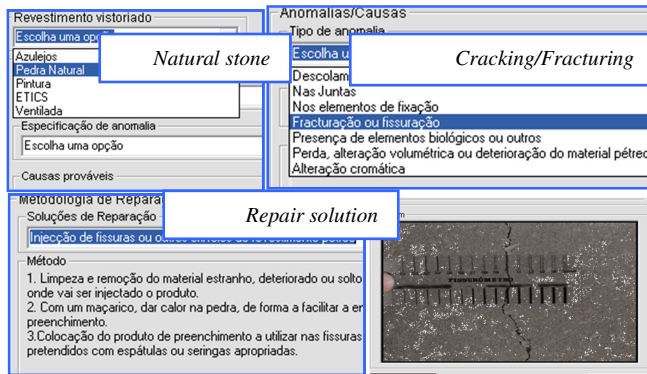


Figure 4: Selecting data in the inspection interface

The repair methodology associated to the selected type of anomaly is also presented. These data are then linked to the element. A report history of inspections is permanently associated to the building so that during any later interaction with the model, the inspection report that was defined using the prototype can be accessed.

To sum up, by 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.

C. The case study

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

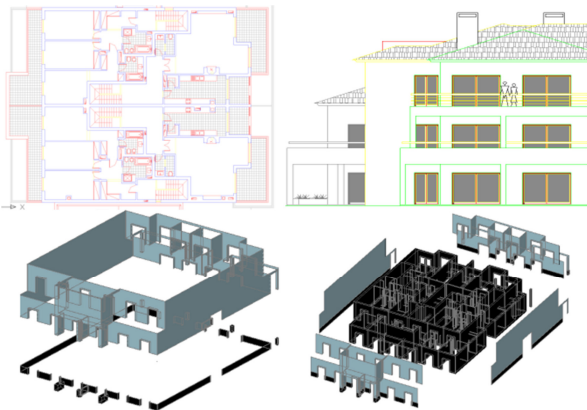


Figure 5: Steps in the geometric modeling process.

All coatings studied were considered in this case-study. Thus the main façade was assumed to be tiled and the remaining façades painted while hall façades are of natural stone. Figure 6 shows how to identify a façade in the virtual model of the building. Figure 7 shows the inspection report of an anomaly.

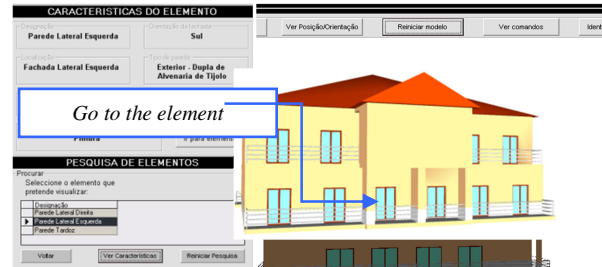


Figure 6: Identification of a façade element.



Figure 7: An inspection sheet report.

III. THE CONSTRUCTION PLANNING 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 [12]. This requires the identification of the client's objectives in terms of usage, function, quality, time and cost, and the establishment of relationships between the people involved, integrating, monitoring and controlling the contributors to the project and their output, and evaluating and selecting alternative solutions in pursuit of the client's satisfaction with the outcome of the project. It is essential, therefore, that the project designer has the depth of knowledge to be able to correctly identify the different stages of the construction planning, as well as to take into consideration the logistics and resources involved in the project. The construction planning used in the implemented prototype is realistic and considers the graphic and written documentation, measurements and quantities map, specifications and regulations relevant to the project [13].

A prototype based on VR technology with application to these demands of construction planning, was created. This interactive virtual model presents the project in 3D, integrated with the construction planning schedule, resulting in a valuable asset in monitoring the development of the construction activity, compared to the construction planning already drawn up. The 4D application allows the time factor to be considered in conjunction with the 3D geometry of the different steps of the construction activity, according to the schedule established for the construction, thus offering a detailed analysis of the construction project. Additionally, VR technology allows the visualization of different stages of the construction and interaction with the real-time construction activity. This application clearly shows the constructive process, avoiding inaccuracies and building errors, thereby facilitating better communication between partners in the construction process.

This application was developed in three stages: planning, modeling, and the integration of the first two stages.

- Planning takes into consideration the final purpose of the presentation, and the definition of tasks; the details, therefore have to be in line with this idea. Using *Microsoft Project 2007*, the tasks are introduced and the relations between them defined;
- Geometric modeling needs to relate correctly to the tasks as defined at the planning stage. Using *AutoCAD 2010* as a modeling tool, the layers make the distinction between the different tasks and elements are created in enough detail to support correct comprehension. The application also presents a real-time illustration of the evolution of the construction through photographs of the site, taken at specific points in time;
- The third stage, integration, makes use of two programs: *EON Studio 5.0* and *Microsoft Visual C# 2008 Express Edition*, where the first takes the 3D model created with *AutoCAD* and introduces it in the application developed using the second.

A. The interface

The application, developed in C#, integrates all the components described with the interface as shown in Figure 8.

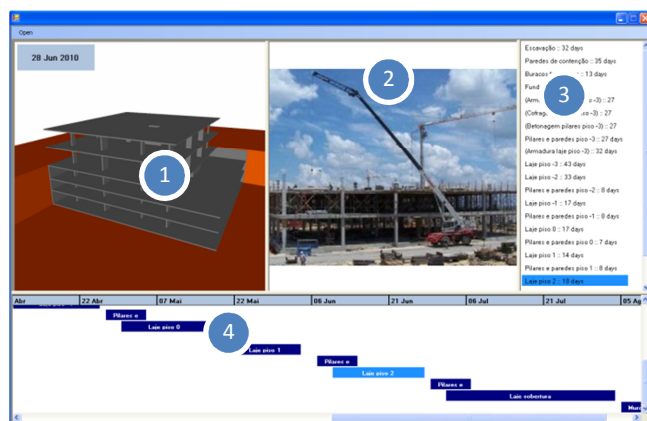


Figure 8: Application interface.

The application his organized as outlined below: Virtual model (1); Pictures of construction site (2); Planning task list (3); Gantt map (4). The interaction with the application is made through 3 and 4. Both the task list items and Gantt map bars are buttons which, when pressed, send the information to the *EON* for the task selected, and in return *EON* presents the model in the current state, that is, it shows and hides specific elements depending on the specific stage of the construction.

EON can interact with the model in a number of different ways. In this prototype only the state of the elements and camera position is changed. The state of an element is presented by its Hidden property, whether it is selected or not, whilst the camera position is determined by translation and rotation coordinates. *EON Studio* also offers the possibility of changing the material associated with each element, creating a more realistic model.

Any new objects can be introduced into the application, just by modeling the new elements considering their positions relative 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 its implementation imperatives are met. Additionally, with the appropriate models, it can also be used in construction site management.

The weakness of this prototype lies in the time needed to carry out the preparation for the actual interaction with the application. Modeling a building may not be very extensive. The programming of the actions in *EON Studio*, however, can be time-consuming.

B. The case study

As a method of testing the application, a construction project was undertaken, more particularly, the structure of a building, using both its graphic documentation, that is, the architectural and structural blueprints, and the project description and construction planning (Figure 9).

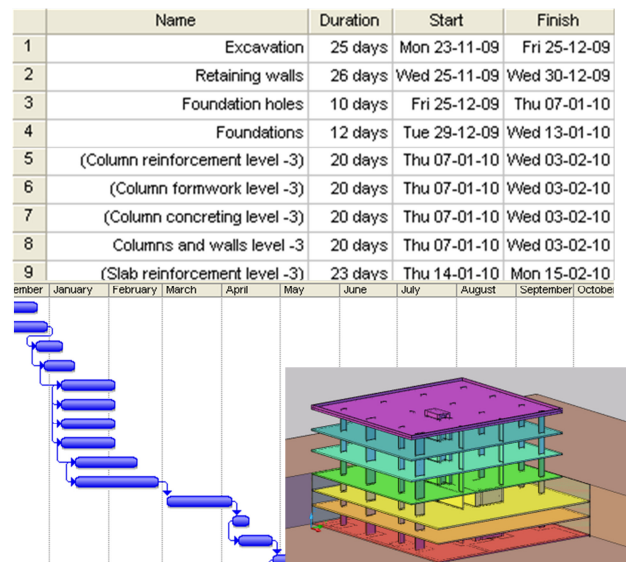


Figure 9: Construction planning (list and Gantt map) and the 3D model of the building structure.

The whole project was simplified to serve this paper's academic purposes: the list of tasks was defined based on the more characteristic stages of a construction process, and a few tasks focused on the construction details of certain elements. As a result, *AutoCAD* layers were created for each task defined and the 3D model constructed. When finished, the 3D model was exported to *EON Studio*, where a diagram of events was created, after which the application was ready to be used.

As explained above, the task list and the virtual model are connected: when selecting a task, the relevant construction stage is presented (Figure 10). The first scenario is the landscape and then the foundation work is shown (Figure 11).

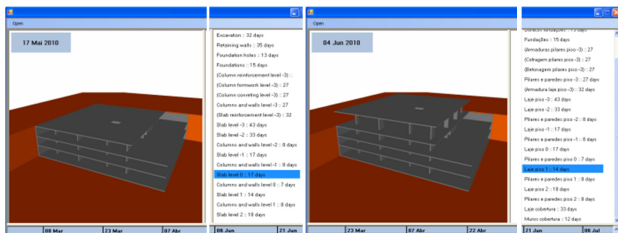


Figure 10: Application's virtual model and task list.

In Figure 11, some construction details have been modeled. Progress across three different stages, of one of the columns, is shown in Figure 12. There being no picture associated, the camera symbol becomes visible instead. A detail of the reinforcement and concrete of a slab is shown in Figure 13.

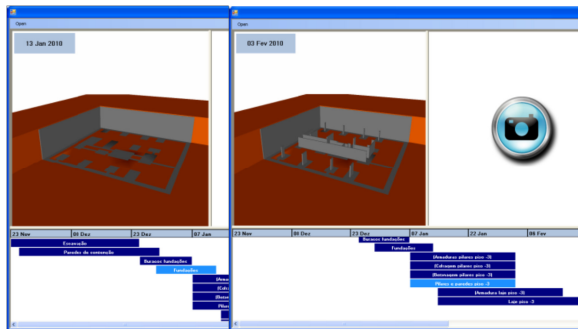


Figure 11: Visualization of the foundation work.

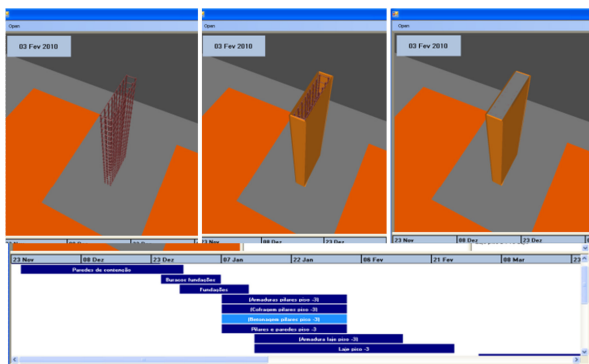


Figure 12: Column construction: reinforcement, formwork and concreting.

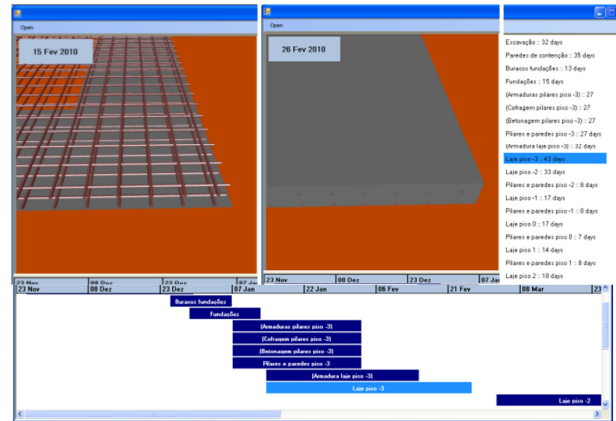


Figure 13: Construction of a slab.

When constructing a building, the planning sometimes needs to be changed due to unexpected occurrences. Implementing these changes in the prototype is actually very simple, as the user has only attribute new start and finish dates to the task in *MS Project* and load the new file into the application.

When a task is selected in the construction planning chart the static position of the model is presented. A first view is always linked to a task. This was established to provide easier interaction with the 3D model, and to focus the attention of the user on the important sections of each task, guiding them through the proper course of development of the construction.

Next, the user can manipulate the virtual model, in order to choose the identical perspective as that shown in the photo. So, with the visualization of what is planned and what has been done in the real building, the construction work can be better compared and analyzed (Figure 14).

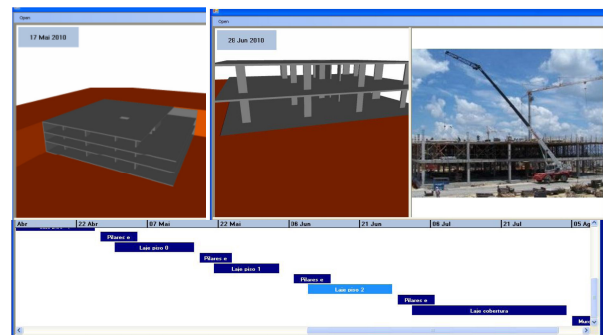


Figure 14: Rotation applied to the virtual model.

In addition by manipulating the model the user can walk through the virtual building observing any construction detail he wants to compare.

All steps have been modelled and linked to the planning chart. Figure 15 shows the details of the construction work. The date for each visualized task is shown in the upper left corner of the virtual model window.

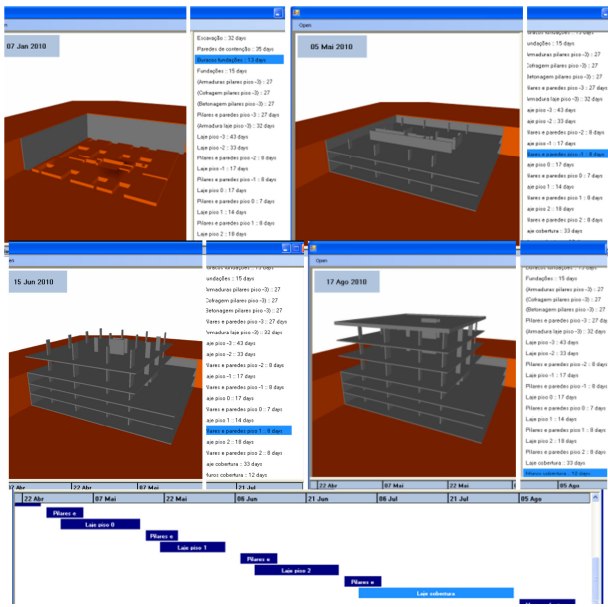


Figure 15: Sequence of the construction process.

IV. CONCLUSIONS

Virtual Reality technology with its capability of interaction and connectivity between elements was 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 database in an interactive environment and has a user-friendly interface with easily manipulation of the data, it engenders 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 can 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 anomalies.

Technical drawings and explanatory texts often have little detail and are frequently insufficient in fully comprehending the object. Using VR models means that mistakes can more easily be caught before construction starts, which translates into 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 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.

Both models support construction activity. The VR construction model allows the presentation of each step comparing what is planned with the real situation observed, the pictures taken *in situ*. The model, therefore, helps the designer and owner to redefine the early plan introducing changes to the work in progress. Thus, economic benefits of updating the planning schedule are achieved along with better, error-free construction with no unnecessary delays.

The maintenance model supports the global analysis of the need for repair tasks in a building, helping the designer to define an adequate plan of rehabilitation work. The plan must incorporate the repair of all anomalies detected during an inspection visit, which are reported, with the help of the VR model, it, too, bringing economic benefits.

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