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# Construction and Maintenance Planning Supported on Virtual Environments

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Additional information is available at the end of the chapter

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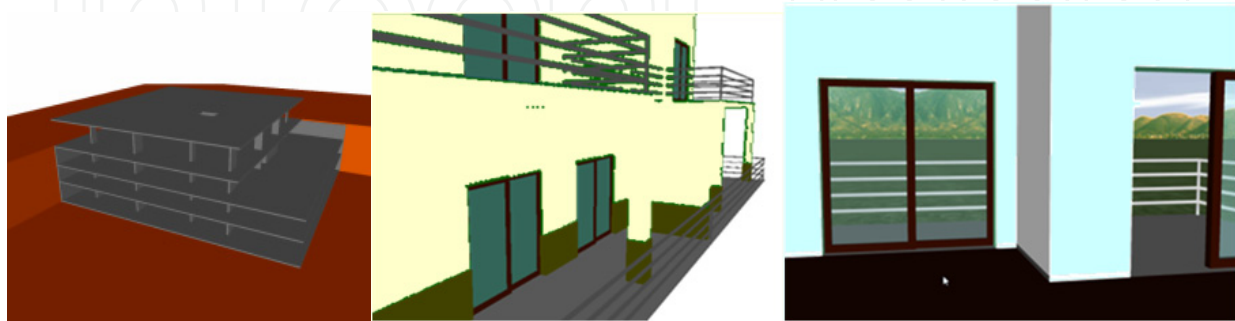
## 1. Introduction

The main aim of a research project (Sampaio and Gomes, 2011), 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 (Sampaio et al., 2009). A second prototype concerning construction planning is now complete (Santos, 2010) and two Virtual Reality (VR) models concerning maintenance of the closure of interior (Rosrio, 2011) and exterior (Gomes, 2010) walls are also finished. This chapter describes these three later models created as part of the overall research project.

Applications based on Virtual Reality technology for use in construction and maintenance planning of buildings were developed (Fig. 1).

- 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 (3D+time) 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.
- 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 behaviour 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.

- A third VR model is an application concerning the maintenance analyses of interior wall allowing the visualization of the degradation over time of the painted elements of a building. The virtual model support the inspection activity helping to choose the anomalies, the provable causes and the most adequate repair methodologies. In addition, a chromatic scale is created and associated with the walls covering elements to evaluate their degradation since they are painted until they reach their expected durability, and needed to be repainted.



**Figure 1.** VR models of construction and coating elements of exterior and interior walls.

This work brings an innovative contribution to the field of construction and maintenance supported by emergent technology. The building lifecycle is in constant evolution, so require the study of preventive maintenance, though, for example, the planning of periodic local inspections and corrective maintenance with repair activity analysis. For this reason, the VR models facilitative the visual and interactive access to results, supporting the drawing-up of inspection reports. 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.

## 2. 4D and VR models in construction

These interactive models integrate 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 the maintenance of the materials used as interior and exterior closures. The principal objective of the interactive VR prototypes is to support decision-making in the area of maintenance planning.

Currently, the management of information related to the maintenance of buildings is based on the planning of action to be taken and on the log of completed work. The capacity to visualize the process can be added through the use of three-dimensional (3D) models which facilitate the interpretation and understanding of target elements of maintenance and of 4D (3D+time) models through which the evolution of deterioration can be visually demonstrated and understood. Furthermore, the possibility of interaction with the geometric models can be provided through the use of VR technology.

Information technology, namely 4D modelling and VR techniques, is currently in use both in the construction activity and in education (Mohammed, 2007). At the Department of Civil Engineering, some didactic models have already been generated. The research project presented in this chapter follows on from that previous educational work: two 3D geometric models which support activity in the rehabilitation of buildings (Sampaio et al., 2006); and three VR models developed to support classes in Civil Engineering (wall, bridge and roof construction) in Technical Drawing, Construction and Bridge disciplines (Sampaio et al., 2010). The didactic VR models are in common use in both face-to-face classes and on an e-learning platform.

In construction industry, from the conception to the actual implementation, project designs are presented mostly on chapter, 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. 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).

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 (Webb and Haupt, 2003).

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 4<sup>th</sup> 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.

The chapter describes both (interior and exterior walls) maintenance models, highlighting the constitution of the database supporting the models, and the organization of a user-friendly interface designed to be used by an inspection worker. During the construction of these models, 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. These prototypes were trailed in an actual project. The lifecycle 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 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.

### **3. 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 (Walker, 2002).

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 (Leinonen et al. 2003).

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 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 modelling needs to relate correctly to the tasks as defined at the planning stage. Using *AutoCAD 2010* as a modelling 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 of the first two stages, makes use of two programs. *EON Studio 5.0* (2010) 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.

### 3.1. Interface

The application, developed in C#, integrates all the components described with the interface as shown in Fig. 2. The application his organized as outlined below: Virtual model; pictures of construction site; planning task list; Gantt map.

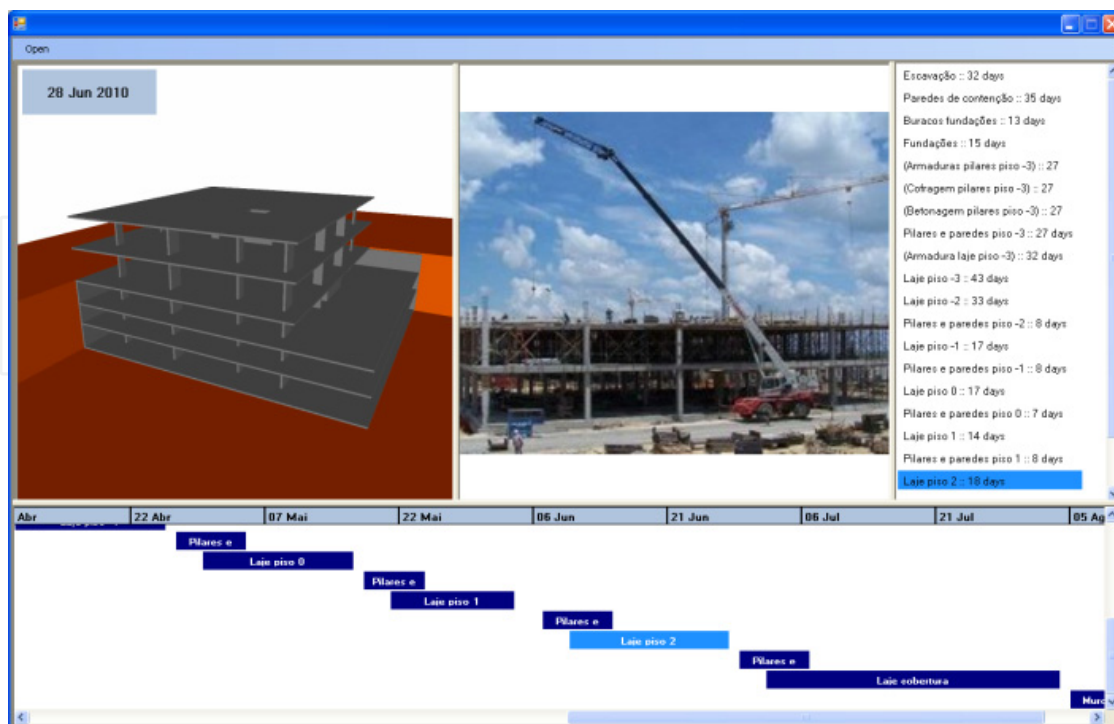


Figure 2. Application interface.

The interaction with the application is made through Planning task list and Gantt map. 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.

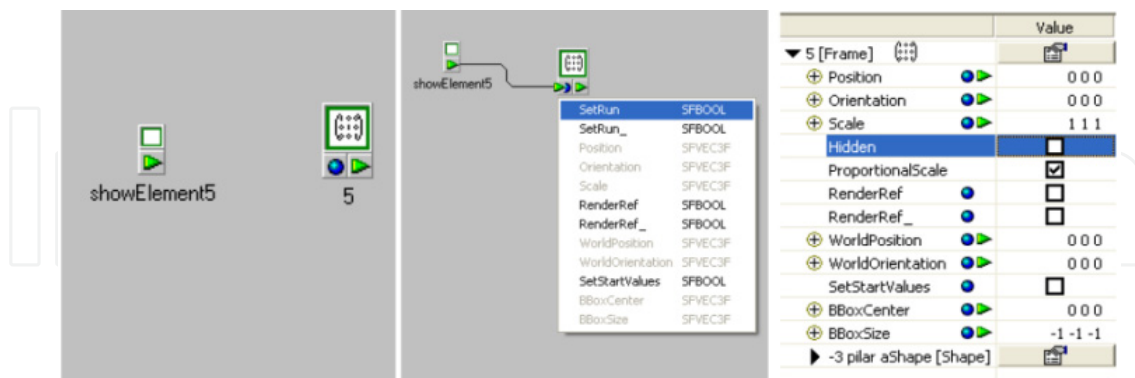
Any new objects can be introduced into the application, just by modelling the new elements considering their positions relative to the ones already in the simulation and programming the associated action in *EON Studio*.

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.

### 3.2. Programming details

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

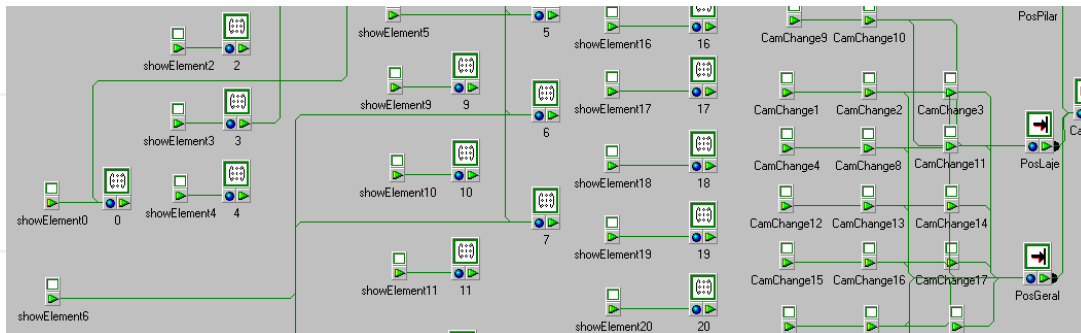
In the application, the geometric model of the building is presented in a sequence simulating the construction activity. For that, each modelled component of the building is connected to the programming instruction: hidden and unhidden (Fig. 3).



**Figure 3.** Hidden and unhidden instruction.

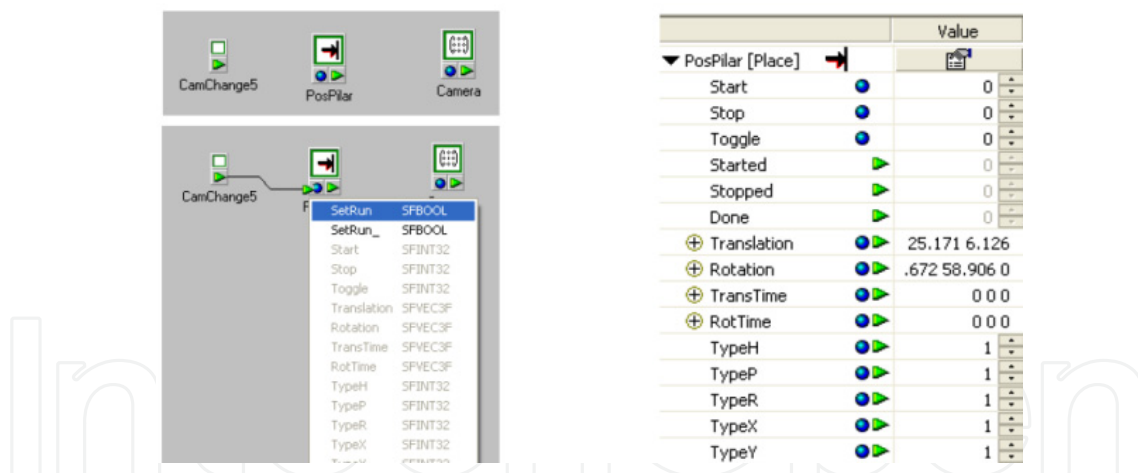
This is one of the capacities allowed by the *EON* software. The command of unhide is linked to each step (label of the list of activities and bar of the Gantt map) and to each geometric model. The identification both in the list/map and the related geometric model is established by a number. The number corresponds to the sequence defined in the design project. An action will begin when the user click over a label or a bar.

Fig. 4 presents a tree of links connecting the command of interaction (executed by the user) and the instruction show of the respective element (see the instruction *showelement\_n* linked to the geometric model identified by the *n* number).



**Figure 4.** Diagram of actions hidden/unhidden for each element and the control of the camera.

In addition the control of the position and orientation of a camera (position, zoom and orientation of the model in relation to the observer) must be defined in accordance with the selected construction step. The position of the camera is controlled within the *EON* software as shown in Fig. 4. A first position of the camera is defined in order to allow the user to visualize adequately the selected detail of the building (Fig. 5). After that the user is free to walkthrough inside and around the model. For that the user must interact with the 3D model through the VR window of the interface.



**Figure 5.** Control of the translation and rotation movements of the model.

### 3.3. Example of application

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 (Fig. 6). The whole project was simplified to serve this chapter’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.



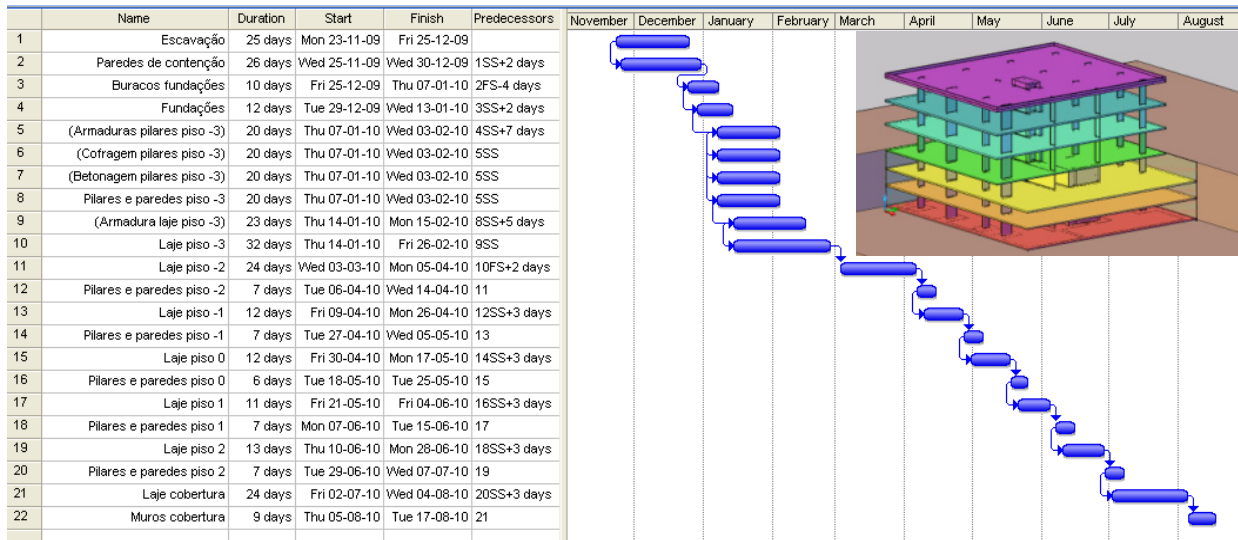


Figure 6. Construction planning (list and Gantt map) and the 3D model of the building structure.

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 (Fig. 7). The first scenario is the landscape and then the foundation work is shown. There being no picture associated, the camera symbol becomes visible instead.

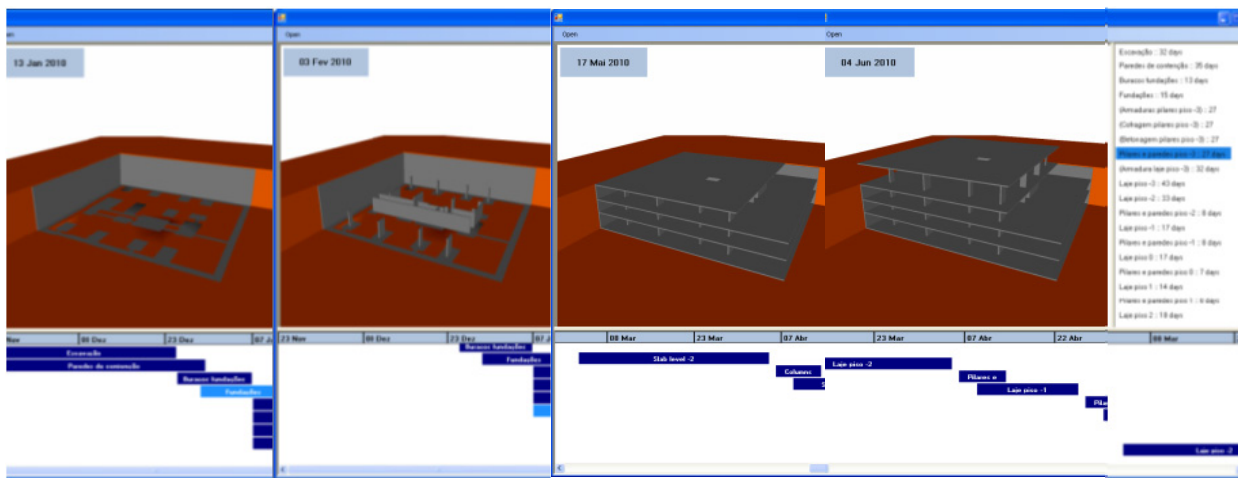
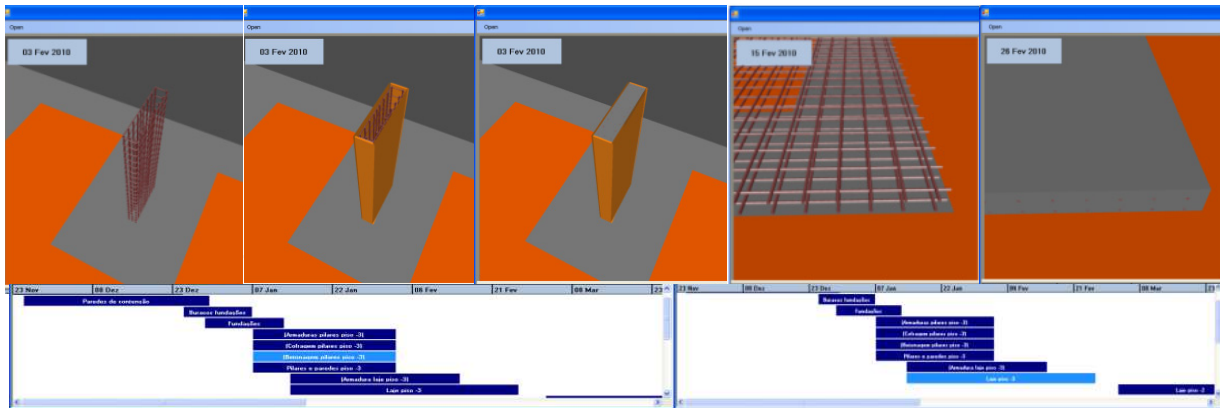


Figure 7. Application's virtual model and task list.

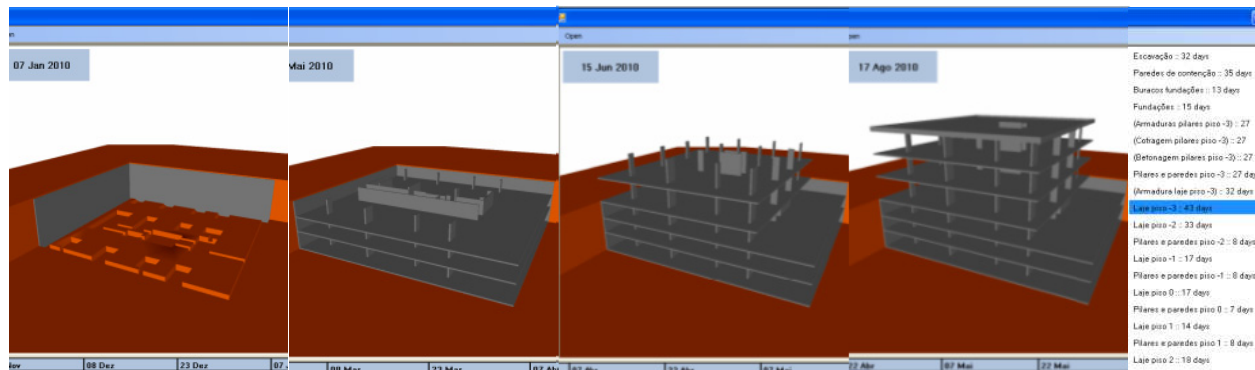
Some construction details have been modelled. Progress across three different stages, of one of the columns and a detail of the reinforcement and concrete of a slab, are shown in Fig. 8.

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 finishes dates to the task in *MS Project* and load the new file into the application.



**Figure 8.** Column and slab construction: reinforcement, formwork and concreting.

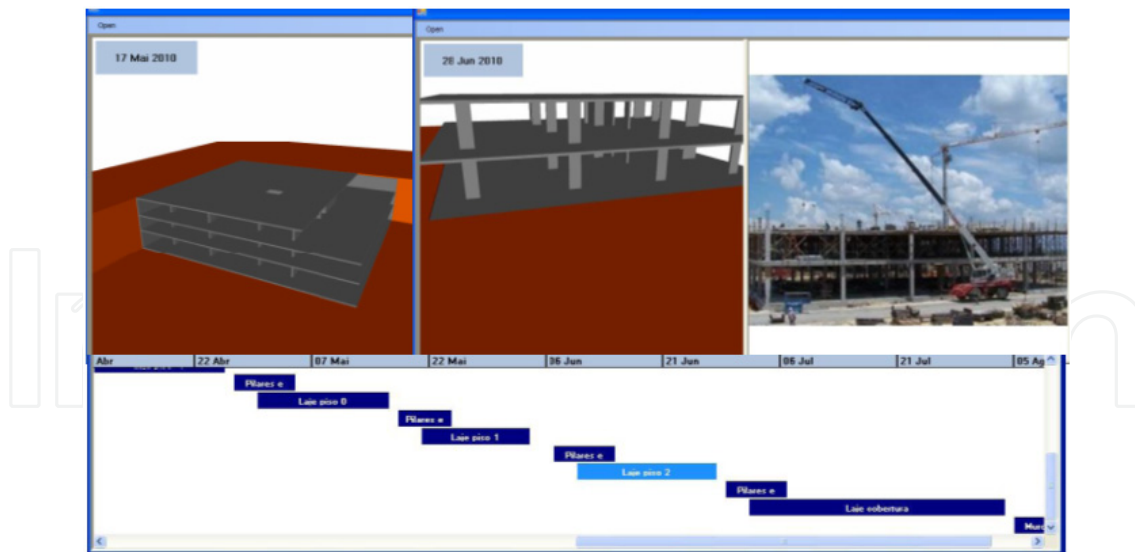
All steps have been modelled and linked to the planning chart. Fig. 9 shows the details of the construction work. The date for each visualized task is shown in the upper left corner of the virtual model window.



**Figure 9.** Sequence of the construction process.

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 analysed (Fig. 10).

In addition by manipulating the model the user can walk through the virtual building observing any construction detail he wants to compare. Comparing with other 4D models the interaction with the present model is not completely allowed and the pictures obtained in the construction place are not linked with the model (Casimiro, 2006). This VR model is more intuitive. So the principal innovative contribution of the model is the incorporation of updated pictures taken in situ. It helps designer to follow adequately the construction process and he can introduce the necessary changes in the construction plan previously established.



**Figure 10.** Rotation applied to the virtual model.

#### 4. Interior wall maintenance model

The coating applied to building walls, naturally, performs an important aesthetic function: it is, however, essentially a protective element for the substrate on which it is applied as far as the action of environmental agents of wear and tear is concerned. The coating is fundamental to a proper overall performance of a building throughout its working life.

Materials frequently used in the coating of ordinary buildings are: paint, varnish, stone and ceramics (Eusébio and Rodrigues, 2009). In Portugal, where interior walls are concerned, the most commonly used coating is paint. It is a multi-purpose material, used under a variety of decorative effects, based on a widely-ranging palette of colours, patterns and textures and is easily applied on any type of surface. In addition, paint, compared to other materials, is less costly, not only as far as the product itself is concerned, but also in its application, since relatively non-specialized labour is required. Nevertheless, as deterioration is a given, maintenance is needed.

Factors such as the constant exposure of the coating to the weather, pollutants and the normal actions of housing use, linked to its natural ageing and, in some cases to the unsuitable application of systems of painting give rise to its deterioration and to the appearance of irregularities, which can negatively affect its performance as both an aesthetic and a protective element. According to Lopes (2004), in normal conditions of exposure and when correctly applied a paint coating can remain unaltered for about five years. Establishing suitable maintenance strategies for this type of coating is based on the knowledge of the most frequent irregularities, the analysis of the respective causes and the study of the most suitable repair methodologies.

The completed virtual model identifies the elements of the building which make up the interior wall coating so that monitoring can take place. The application is supported by a database, created for the purpose, of irregularities, their probable causes and suitable repair

processes, which facilitates the inspection process. The information is recorded and associated to each monitored element, allowing subsequently, the inspection and repair activity log to be consulted, thus providing a tool for the definition of a rehabilitation strategy. In addition, the model assigns a colour to each of the coating elements, the colours defined by the time variable, so that the evolution of the deterioration of the coating material is clearly shown through the alteration in colour. The prototype is, then, a 4D model.

The model integrates a virtual environment with an application developed in Visual Basic programming language. This allows interaction with the 3D model of buildings in such a way that it becomes possible to follow the process of monitoring the coating elements, specifically, painted interior walls, in terms of maintenance, throughout the life-cycle of the building.

#### **4.1. Maintenance**

The General Regulations for Urban Buildings (RGEU, 1951) applied in Portugal, stipulates the frequency of maintenance work, stating that existing buildings must be repaired and undergo maintenance at least once every eight years with the aim of eliminating defects arising from normal wear and tear and to maintain them in good usable condition in all aspects of housing use referred to in that document.

The time-limit indicated is applicable to all elements of the buildings generally. It is clear, however, that the regulatory period is too long for some specific components and that, frequently enough, the time-limits for action are not respected. There are, too, inefficient rent policies, leading to long periods without rehabilitation, and that the prevailing culture is one of reaction on the part of the various parties involved in the maintenance process. To these aspects should also be added the defects sometimes registered during the construction of property developments, exacerbating the poor state of repair of the buildings. This gives rise to numerous irregularities which, in turn, frequently leads to inadequate safety conditions.

According to Córias (2009), the purpose of maintenance is to prolong the useful life of the building and to encourage adherence to the demands of safety and functionality, keeping in mind the specific set of conditions of each case and its budgetary considerations. Satisfactory management of this activity is carried out by putting into practice a maintenance plan which must take into consideration technical, economic, and functional aspects arising with each case.

Collen (2003) points out that investment in the maintenance and rehabilitation sector in Portugal is still weak compared to that in the same sector in the construction industry in the other countries of the European Community. She makes it clear, however, on a more positive note, that some measures have already begun to be implemented here: some urban regeneration programs have been created, legislation, which focuses on the sustainability of buildings, has been laid down, and the revision of constructive solutions has been carried

out, all with the objective of guaranteeing that the maintenance of built heritage be an integral part of the construction sector.

The maintenance of buildings, then, is an activity of considerable importance within the construction industry; its contributory aspects of conservation and rehabilitation work need to be supported by correct methodologies of action, underpinned by scientific criteria and by suitable processes for the diagnosis of irregularities and the evaluation of their causes. This chapter aims to make a positive contribution to this field using the new computer technology tools of visualization and interaction.

## 4.2. Pathologies in paint coatings

The technical document *Paints, Varnishes and Painted Coatings for Civil Construction* published by The National Laboratory for Civil Engineering (LNEC) (Eusébio and Rodrigues, 2009), defines paint as a mixture essentially made up of pigments, binder, vehicle and additives. It has a pigmented, pasty composition, and when applied in a fine layer to a surface, presents, after the dispersion of volatile products, the appearance of a solid, collared and opaque film (Farinha, 2010).

The durability of the painted coating depends on the environment in which it is used, and on the surface it is applied to as well as the rate of deterioration of the binder in the paint. The influence of the environment is the result of the action, in conjunction or alone, of a variety of factors such as the degree of humidity, the levels of ultraviolet radiation, oxygen, ozone and alkalis, variations in temperature and of other physical or chemical agents whose effect depends considerably on the time taken to apply it (Marques, 1985). When their influence is not counteracted or minimized, imperfections can arise in the coating film, such as, the appearance of defects in the layer or paint with the loss of functionality where the desired aim of the application is concerned.

These irregularities manifest themselves in various ways and in different degrees of severity. Based on the study made of the causes of the defects, specific methodologies for their resolution were established. Fig. 11 shows common defects in painted interior walls.



**Figure 11.** Swelling, efflorescence, cracking and blistering (Moura, 2008).

The information gained from the pathological analysis of this type of coating was used to draw up a database supporting the interactive application. These data support the creation of inspection files related to the elements which are monitored in each case studied.

In order to form a user-friendly database of relatable data, groups of pathologies, shown below in Table 1, were considered. This classification provides the required automatism of access to the database and supports the presentation of synopses of the causes and repair methodology inherent in each pathology.

Classification	Irregularity	Repair methodology
Alteration in color	Yellowing	- Cleaning the surface and repainting with a finish both compatible with the existing coat and resistant to the prevailing conditions of exposure in its environment
	Bronzing	
	Fading	
	Spotting	
	Loss of gloss	
	Loss of hiding power	
Deposits	Dirt pick-up and retention	- Cleaning the surface.
	Viscosity	
Changes in texture	Efflorescence	- Removal by brushing scraping or washing; - repainting the surface; - When necessary apply sealer before repainting.
	Sweating	
	Cracking	
	Chalking	
	Saponification	
Reduction in adhesion	Peeling	- Proceed by totally or partially removing the coat of paint; - Check the condition of the base and proceed with its repair where necessary; - Prepare the base of the paint work.
	Flaking	
	Swelling	

**Table 1.** Classification of irregularities.

During the process of an on-site inspection, the user of the application can refer to the database in order to classify the abnormality being observed, consulting the list of defects, which includes, in addition to their identification, the most relevant characteristics and some of the causes that could be at the root of their development. Table 2 lists two of the irregularities from the classification: *Alteration in colour*.

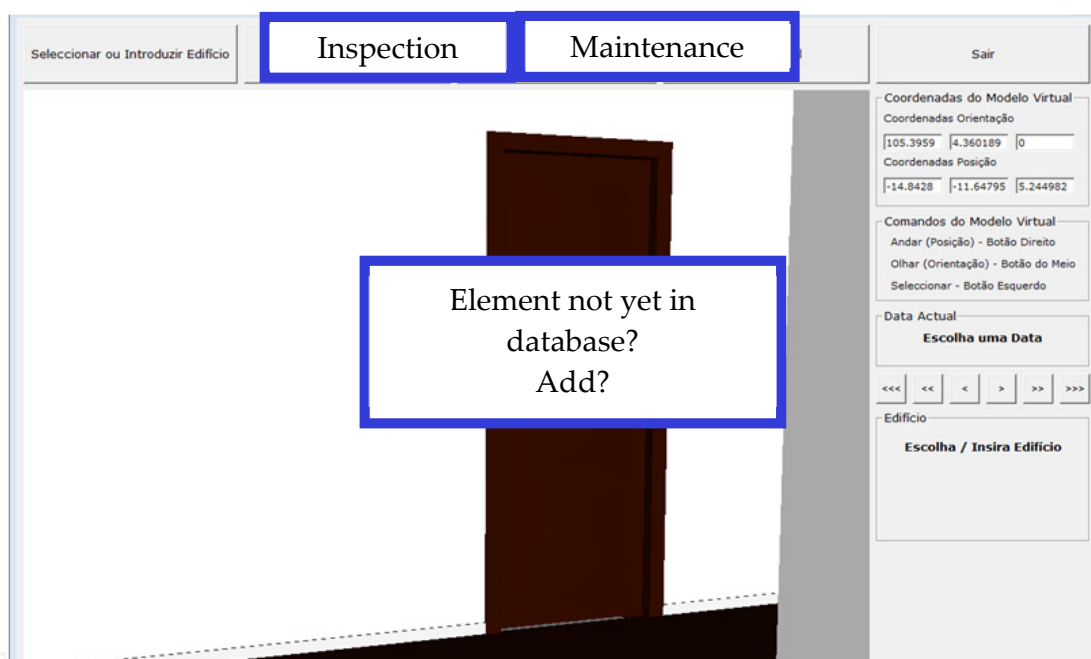
Classification	Irregularity	Characteristics and causes
Alteration in colour	Yellowing	- A yellow colour caused by ageing of the film of the paint or varnish; - Action of environmental agents (solar radiation, temperature oxygen and humidity) on the binder in the paint provoking changes in its molecular structure.
	Discoloration	- Partial loss of colour of the film of paint coating; - Action of environmental agents (solar radiation, temperature, polluted atmosphere and chemically aggressive bases of application) on the binder and/or the pigments of the painted coating.

**Table 2.** Irregularities and Causes.

### 4.3. Interactive model

The completed application supports on-site inspections and the on-going analysis of the evolution of the degree of deterioration of the coating. The following computational systems were used in its development: *AutoCAD*, in the creation of the 3D model of the building; *EON Studio* (2010), for the programming of the interactivity capacities integrated with the geometric model; *Visual Basic 6* in the creation of all the windows of the application and in the establishment of links between components. All the systems were made available by the *ISTAR/DECivil* (2011), of the Technical University of Lisbon (TUL).

The main interface gives access to the virtual model of the building and to the inspection and maintenance modules (highlighted in Fig. 12). The first step is to make a detailed description of the building (location, year of construction, type of structure....., Fig. 13) and representative modelled elements of the interior wall coating, so that they can be monitored.



**Figure 12.** The main interface of the virtual application.

The model is manipulated in the virtual environment by using the mouse buttons (movement through the interior of the model and orientation of the camera, Fig. 13). The coordinates of the observer's position and the direction of his/her point of view are associated with the element during the process of identification. Thus, later, when an element in the database of the application is selected using the interface, the model is displayed in the visualization window so that the target coating can be observed.

Walking through the model with the aim of accessing all the elements of the building, the user needs to be able to go up and down stairs or open doors or windows. The virtual model has been programmed, using the *EON system*, in such a way that these capacities are activated by positioning the cursor over the respective objects, in that way, the user is able to walk through the whole model.

The screenshot shows a form with the following elements:

- Characteristics of the building:** Fields for 'Código Postal' (2750 000), 'Localidade' (Cascais), and 'Tipo de Utilização' (Habitação).
- Coordinates of the virtual model:** 'Coordenadas Posição' fields with values -14.8428, -11.64795, and 5.244982.
- Orientation of the virtual model:** A section with buttons 'Olhar (Orientação) - Botão do Meio' and 'Seleccionar - Botão Esquerdo'.
- Other fields include 'Rua / Avenida / Praça / Largo' (Av. Marginal), 'Lote' (100), and 'Andar'.
- Buttons at the bottom include 'Limpar Tudo', 'Validar', and 'Voltar'.

**Figure 13.** Interface for the detailed description of the building and coordinates and manipulation commands in the virtual model.

Each wall surface in each of the rooms of the house is a component which has to be monitored and, therefore, to be identified. Using the model, the user must click the mouse on an element, and the message New Element is shown (highlighted in Fig. 12). Associated to this selected element is the information regarding location within the house (hall, bedroom), wall type (simple internal masonry wall) and coating (paint).

#### 4.3.1. Making an inspection

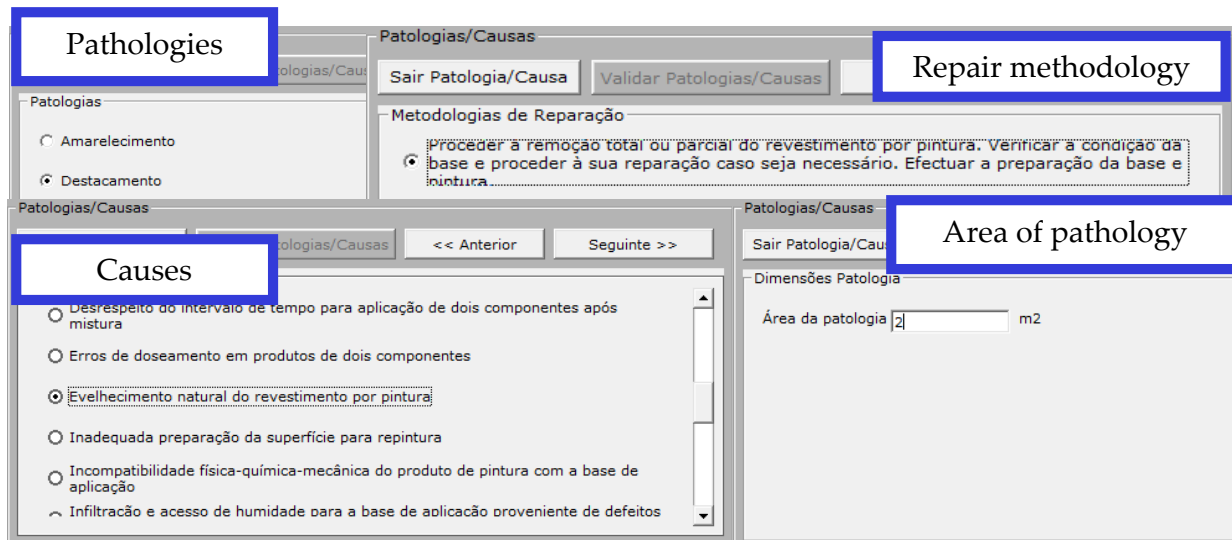
Later, on an on-site inspection visit, the element to be analysed is selected interactively on the virtual model. The inspection sheet (Fig. 15) is accessed by using the Inspection button which is found in the main interface (Fig. 12). The data which identify the selected element are transferred to the initial data boxes on the displayed page (Fig. 14).

The screenshot shows an inspection sheet with the following elements:

- Inspect new element:** A button at the top left.
- Case history:** A button at the top right.
- Number of pathologies:** A button in the middle right area.
- Data Entry Fields:** 'Tipo de Parede' (Interior), 'Revestimento' (Tinta), 'Data da Inspeção' (01-07-2009), and 'Responsável' (Daniel Rosário).
- Características:** 'Parede simples de alvenaria'.
- Patologias / Causas / Metodologias de Reparação:** A text box containing: 'PATOLOGIA: Destacamento', 'CAUSA: Aplicação de produtos de pintura sobre bases de aplicação lisas e rígidas', and 'METODOLOGIA: Proceder à remoção total ou parcial do revestimento por pintura. Verificar a condição da base e proceder à sua reparação caso seja necessário. Efectuar a preparação da'.
- Fotografias:** A photograph showing a wall with peeling paint, with navigation buttons below it.

**Figure 14.** Presentation of the information introduced into the inspection sheet.






**Figure 15.** Interface for the selection of the irregularity, probable cause, area and repair methodology.

Next, using the database, the irregularity which corresponds to the observed defect, with its probable cause (ageing) and the prescribed repair methodology (removal and repainting) is selected (see highlighted area, Fig. 15). The current size of the pathology should also be indicated since it reveals how serious it is (*area of pathology*, Fig. 15). In the field *Observations*, the inspector can add any relevant comment (Fig. 14), photographs obtained on site can also be inserted into the inspection window and the date of the on-site visit and the *ID* of the inspector should also be added. Several different irregularities in the same coating can be analysed (field *Number of pathologies*, Fig. 14) and other elements can be analysed and recorded and defects observed. Later, the files thus created, associated to each of the virtual model elements, can be consulted (*Case history* button in the Interface in Fig. 14). This same window allows all the data referring to the building and to the completed inspection to be shown, in *pdf* format (Fig. 16).

#### 4.3.2. Maintenance monitoring

How long the working life of any construction component might be is an estimate and depends on a set of modifying factors related to their inherent characteristics of quality, to the environment in which the building is set and to its conditions of use (Webb and Haupt, 2003). In maintenance strategy planning the probable dates when adverse effects might occur in each of these elements must be foreseen, and the factors which contribute to defects must be reduced and their consequences minimized.

The completed model allows the user to monitor the evolution of wear and tear on the paint coating in a house. For this, technical information relative to the reference for the paint used, its durability and the date of its most recent application must be added (Fig. 17) to each element through the Maintenance Interface (also accessed from the main interface, Fig. 12).

FICHA DE INSPECÇÃO		
<i>Inspection sheet</i>		
Dados do Edifício		
<i>Element details</i>		
<i>Location: Hall 1</i>		
<i>Type of wall: Interior</i>		
<i>Description Details: Simple masonry wall</i>		
<i>Coating: Paint</i>		
Dados do Elemento		
Localização	Hall1	
Tipo de Parede	Interior	
Características	Parede simples de alvenaria	
Revestimento	Tinta	
Patologias / Causas / Metodologias de Reparação		
<i>Pathologies/Causes/ Repair Methodologies</i>		
<i>Pathology: Peeling</i>		
<i>Cause: Natural ageing of paint coating</i>		
<i>Repair methodology: Total or partial removal of paint coating. Check condition of the base and repair as necessary. Carry out the preparation of the base and</i>		
<i>Observations: No relevant observations to be recorded</i>		
<i>Manager:</i>		

**Figure 16.** Inspection sheet.

Based on these data, it is possible to link in the date the virtual model is consulted and visualize, in the geometric model, the level of wear and tear as a function of time (see state of repair, Fig. 17). The period of time between the date indicated and the date when the paint was applied is compared to the duration advised, in the technical literature, for repainting. The value given for this comparison is associated to the Red, Green, Blue (RGB) parameters which define the colour used for wall in the virtual model (Fig. 18).

In this way, the colour visualized on the monitored wall varies according to the period of time calculated, pale green being the colour referring to the date of painting and red indicating that the date the model was consulted coincides with that advised for repainting (Fig. 18). The data for painting and repainting are saved to a list of coating elements to be monitored in the virtual model. When an element is selected from this list, the corresponding element is represented in the virtual model, through the preview window, in the colour that corresponds to the period of the consultation.

Technical and commercial characteristics

Tipo  
Interior

Características / Estado de Manutenção

Durabilidade 4 Anos Info

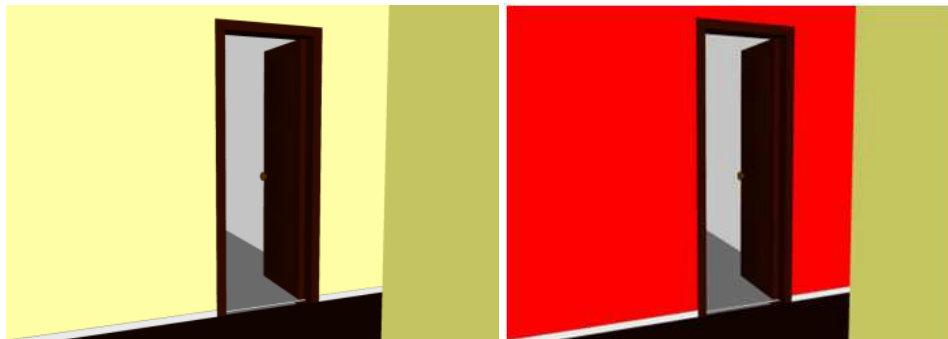
Data da Última Pintura 01-10-2006 Alterar

Data Prevista para a Próxima Pintura 30-09-2010 Alterar

State of repair

Salvar

**Figure 17.** Technical characteristics and the durability of the paint-work.



**Figure 18.** Chromatic alteration of the coating according to its state of deterioration.

## 5. Façade 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 (Gomes and Pinto, 2009) (Fig. 19):

- *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..




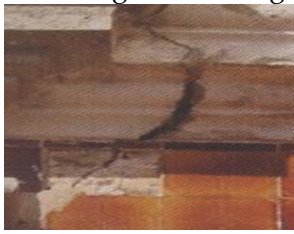
**Figure 19.** Different types of materials applied as façade coatings and some irregularities.

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 (Ferreira et al., 2009);
- 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 (Veiga and Malanho, 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.

## 5.1. 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 3).

Anomaly	<p style="text-align: center;">Detachment</p> 	<p style="text-align: center;">Cracking / Fracturing</p> 
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"> <li>1. Removal of the tiles by cutting grinder with the aid of a hammer and chisel;</li> <li>2. Timely repair of the support in areas where the detachment includes material constituent with it;</li> <li>3. Digitizing layer of settlement;</li> <li>4. Re-settlement of layer and tiles.</li> </ol>	<ol style="list-style-type: none"> <li>1. Removal of the tiles by cutting grinder;</li> <li>2. Removal of material adjustment in the environment and along the joint;</li> <li>3. Repair of cracks, clogging with adhesive material (mastic);</li> <li>4. Settlement layer made with cement in two layers interspersed with glass fibre;</li> <li>5. Re-settlement of layer and tiles</li> </ol>

**Table 3.** Example of anomalies and the associated repair solution.

## 5.2. 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* and VR technology based software, *EON Studio*.

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 (Fig. 20).

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.

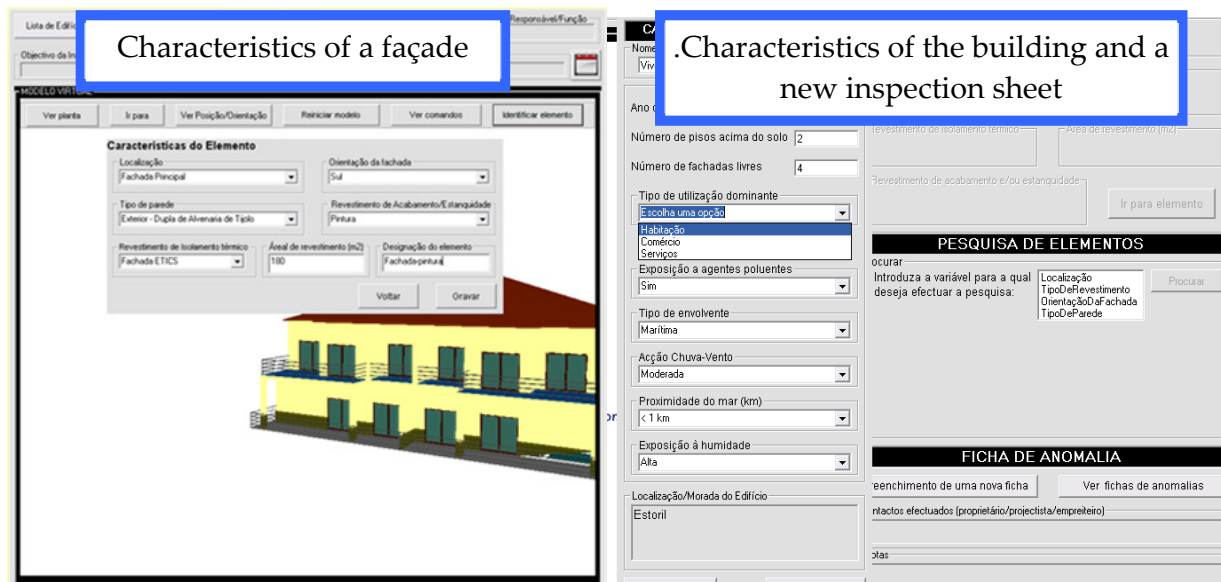


Figure 20. The main interface of the interactive application.

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 (Fig. 21). The inspection sheet includes the type of covering (natural stone, Fig. 22), the anomalies (Cracking /Fracturing) and a list of possible causes to be selected and associated to the element. Several photos can be added.

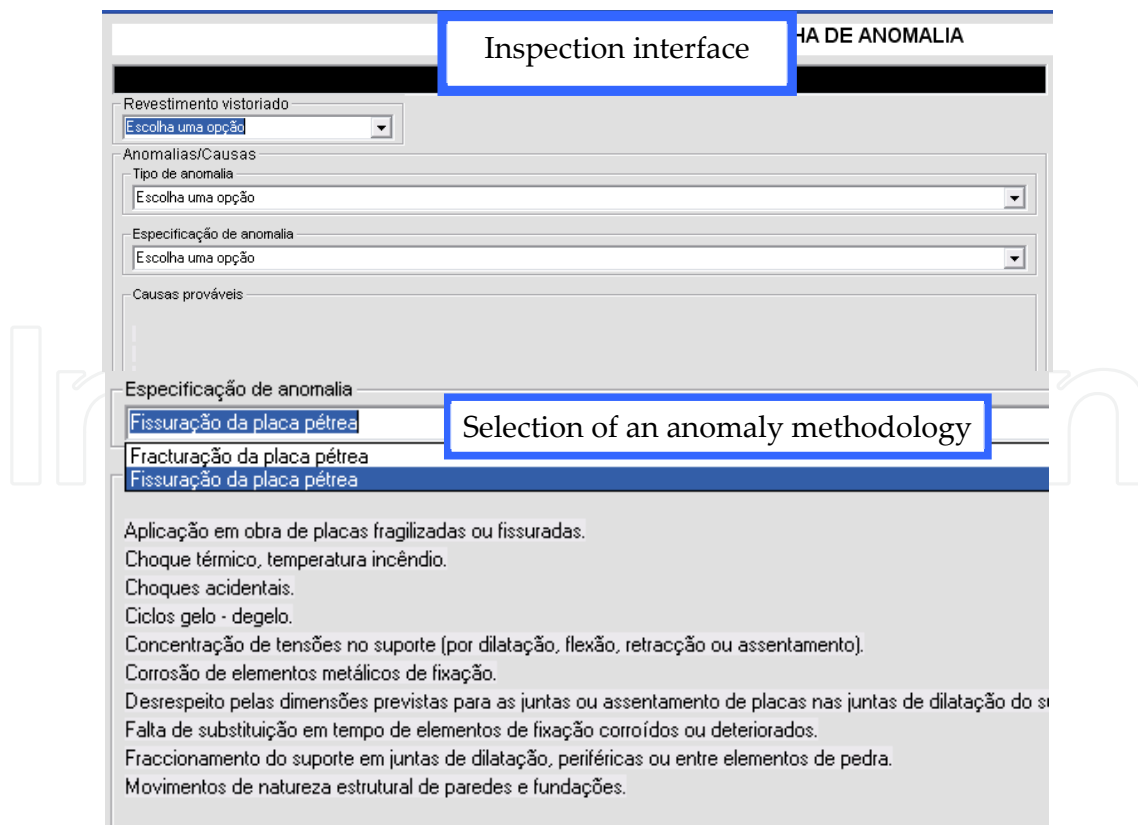


Figure 21. Inspection sheet interface.

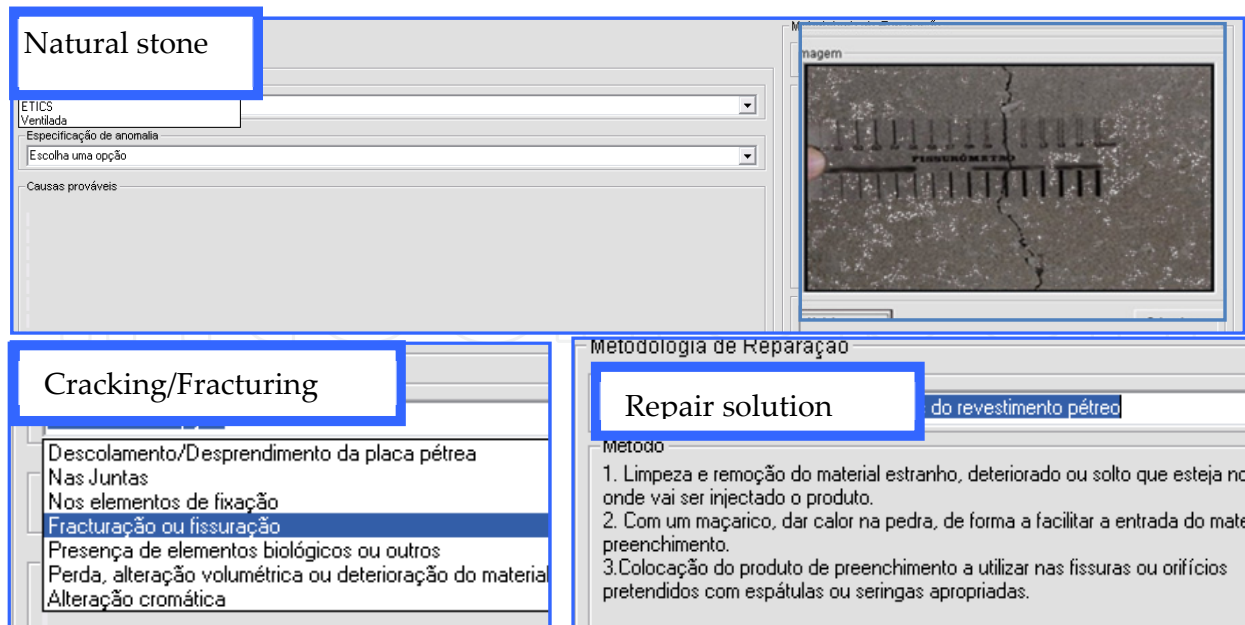


Figure 22. Selecting data in the inspection interface.

### 5.3. Case study

First, the 3D geometric model of a building was created (Fig. 23). In this case, the building consists of a ground-floor, a 1<sup>st</sup> floor and an attic with dwelling space. The coating elements of the walls were then modelled 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.

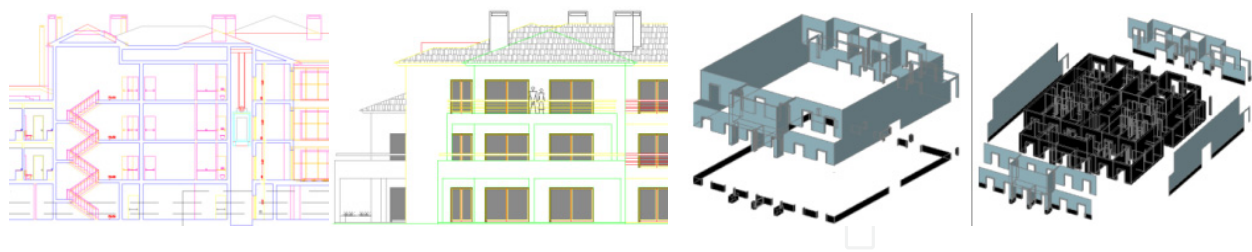


Figure 23. Steps in the geometric modelling process.

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. Fig. 24 shows how to identify a façade in the virtual model of the building.

Fig. 25 shows the inspection report of an anomaly. 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.

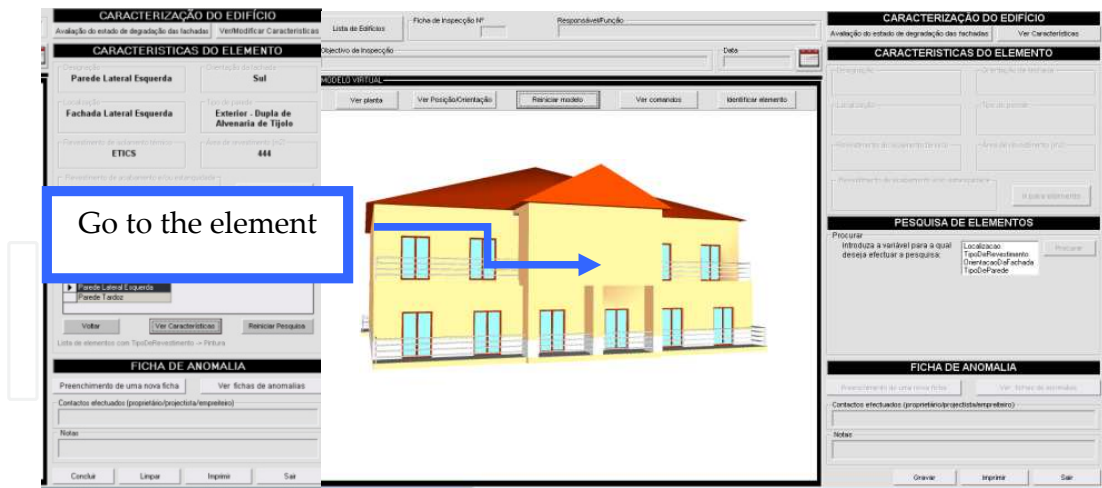


Figure 24. Identification of a façade element.

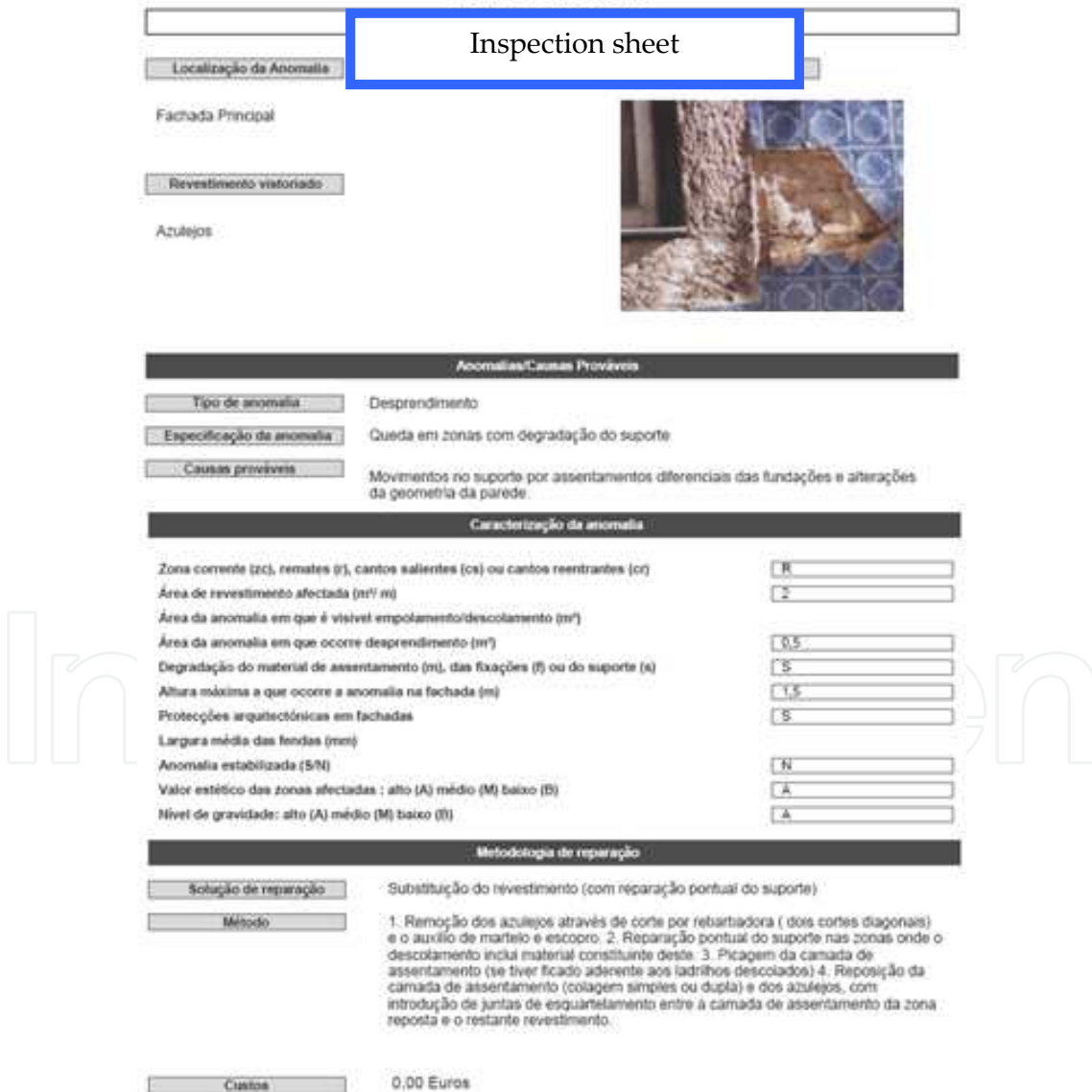


Figure 25. An inspection sheet report.



## 6. Benefits of VR models in construction and maintenance

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.

The developed VR models to support the maintenance of walls interior and exterior enables the visual and interactive transmission of information related to the physical behaviour of the elements. As the VR models are linked to each database in an interactive environment and have user-friendly interfaces with easily manipulation of the data, they engender collaborative systems. With these applications, the user may fully interact with the programs referring to the virtual models at any stage of the maintenance process and can analyse the best solution for repair work. They can also support the planning of maintenance strategies. The main aim of the application is to facilitate maintenance enabling the rapid and easy identification of irregularities, as well as the possible prediction of their occurrence through the available inspection record. This analysis has been shown as playing an important role in conservation and in the reduction of costs related to the wear and tear of buildings and contributes to the better management of buildings where maintenance is concerned. 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.

In addition to the inspection component, a maintenance component was developed which, being visualized in a VR environment, as well as being highly intuitive, facilitates the analysis of the state of repair of buildings. By means of a chromatic scale applied to the monitored elements, displayed in the walk-through of the geometrically modelled building, it is possible to identify the elements which, predictably, will need timely action. With the possibility of altering the time parameter freely, the user can carry out this analysis either for past instants or for future events, being able, in this way, to forecast future operations. This capacity of the model, therefore, contributes to the avoidance of costs associated to irregularities which, with the passage of time, become more serious and therefore more onerous.

The use of new mobile technologies could move the application to the construction site, clarifying any doubts about location or position of each component. As each 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 these applications, the user may fully interact with the programs referring to each virtual model at any stage of the construction and maintenance processes and can analyse the best solution for alternative to construction plane and repair work. The maintenance applications can also support the planning of maintenance strategies and promote the use of IT tools with advanced graphic and interactive capabilities in order to facilitate and expedite the inspection process. The virtual model, moreover, allows users to see, in the virtual environment, the state of repair of the coating.

Two other VR models are now in progress, concerning the inspection activity of floors and roofs of buildings. With these two other modules the research project will be complete. Then the complete VR application will support different aspects of the maintenance process in buildings.

## 7. 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 construction and maintenance domain.

The 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.

Both maintenance models show the characteristics of each element of the building in the model and the information related to inspection, anomalies and repair works. The information about pathologies, causes and repair methods, collected from a specialized bibliography, has been organized in such a way as to establish a database to be used as a base for the drawing up of a tool to support building maintenance.

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