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DURABILITY DAMAGE INDICATOR IN BIM ENVIRONMENTS

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ABSTRACT

As Building Information Modelling (BIM) is being increasingly adopted through private businesses in the Architecture, Engineering, Construction, and Operation (AECO) Industries, new tools, procedures, and functionalities appear. In the last years, BIM has proven its advantages by providing benefits to professionals and guiding them towards a new horizon. Currently, the industry is changing in the Spanish market, and refurbishment projects are more demanded than construction projects involving the design of buildings from scratch. As Spanish housing stock grows older, durability and damage in existing structures need to be analyzed during the refurbishment project's early stages. Structural durability is a critical factor in extending the life span of a building and improving the industry's sustainability. This paper presents a tool integrated into BIM environments that can evaluate the durability index in a specific structural element based on data from a visual inspection. This automated analysis shows if any damage is caused by durability factors, such as steel rebar corrosion, and how much time is left until the damage is critical. This tool enables new functionality in BIM environments to control durability and determine when it is critical to rehabilitating the structure.

KEYWORDS

BIM; durability; carbonation; building assessment; building renovation.

1. INTRODUCTION

The architecture, Engineering, and Construction Industry (AEC Industry) has an essential social duty as one of the most contaminating industries in the world. Climate change is a reality, and sustainability demands are increasing. To correspond to this social demand and the 17 Sustainable Development Goals defined by the United Nations, resource consumption needs to be diminished and materials service life enlarged. Considering only the construction, operation, and demolition phases of the buildings, 15% of the world's freshwater resources, 36% of the world's energy; and about 40% of the world's greenhouse gas emission is consumed by the Industry (Crawford, 2011). Buildings have an average life span of fifty years, and most of the time is spent during the operation phase, with its environmental impact directly related to proper operation and maintenance.

Building renovation is key to reducing environmental impact as it has a double effect on service life. On one side, energy consumption during the operation phase is directly reduced, and the building performs at its prime for more time. On the other side, by increasing the life span of buildings with renovations, fewer new buildings are needed for the population reducing the impact caused by construction.

1.1. Spanish Building Market

In September 2008, Spain entered one of its worst economic crises after the collapse of the building market. The construction of new residential buildings has been reduced drastically since that point, shown by a shift in the revenue from the business. In 2003 the business volume from the construction of new buildings in Spain was 78% (115.841,36 million euros) and 22% (32.615,76 million euros) for restoration and conservation. In 2019 the amounts were 49,1% and 50,9% (43.728,53 and 45.386,53 million euros) respectively ("Observatorio de Vivienda y Suelo. Boletín anual 2020," 2020). The crisis has changed the investment from construction to renovation.

The decrease in construction has caused an older building market in Spain. Due to the reduction in construction from the economic crisis, only 6,5% of the buildings are less than ten years old, while 61,9% are older than thirty years. As the building market grows older, renovation and maintenance are gaining importance, as the buildings present more pathologies. Older buildings require maintenance to extend their service life and meet users' demands. Structural elements directly compromise service life and in the last 12 months, 7.3% of building renovations affected the structure in some way ("Observatorio de Vivienda y Suelo. Boletín especial sobre Rehabilitación 2021," 2021).

The aging buildings in the Spanish market and the necessities to renovate buildings over buildings new ones make building assessment and performance analysis a necessity for the AEC Industry. New social demands for sustainability and an older building market are increasing the necessity to determine the conservation state of a building accurately. Building Conservation Analysis (BCA) is the base for maintenance and management solutions for existing buildings (Matos et al., 2021).

1.2. Building Performance and BIM

Building Information Modeling (BIM) has proven to improve different building performance analyses thanks to its functionalities in recent years. Several Building Simulation Tools (BPS Tools) has been designed in the last years for different building performance analysis related to sustainability assessment (Carvalho et al., 2021; Eleftheriadis et al., 2017; Wu Wei and Issa Raja R. A., 2015), life cycle analysis (Alwan et al., 2021) and multicriteria decision-making (Tan et al., 2021) among others.

BIM advantages for Building Performance Analysis are based on the abilities for interoperability inside these environments. BIM can act as a database storing every parameter of the building and its relations, which can be used to automate analysis processes. These can also be used to create time-related relations among different parameters.

Despite the difficulty of creating a geometrically accurate BIM model of an existing building, these analysis features have been significantly used and have resulted in historical and patrimonial buildings. BIM for Historical buildings (HBIM) utilizes point cloud technologies to overcome this difficulty (Pocobelli et al., 2018) and perform the analysis. Several experiences have been found in the bibliography to perform this kind of analysis on historical buildings, such as Seville's Cathedral (Angulo and Castellano-Román, 2020), the New Theatre of the city of Bologna (Massafra et al., 2020), Four Courts building in Dublin (Dore et al., 2015), Yingxian Wood Pagoda (Jiang et al., 2020) and Flaminio Stadium in Rome (Di Re et al., 2021) among others. The growing interest in BIM by the AEC industry professionals and its capabilities to perform BCA make these environments ideal for building renovation.

1.3.Degradation processes in concrete structures

Maintenances is the main prevention to improve a buildings service life. In concrete structures, it comes from preserving the elements from their degradation processes. Several sources define concrete aging. This degradation can come from pathologies, damage during its life, or simply time passing, and several causes usually interact.

Degradation processes are considered with the Limit State theory in different structural codes. Service states represent different ways to control and prevent these aging processes. Smaller cracking width prevents a quick degradation process by controlling the number of pathogens affecting the reinforced concrete structure and rebars. Cover requirements protect the rebars from early oxidation, lowering their effect and reducing the structure's life span. Among these different degradation procedures, carbonation is constant, affecting the element from the beginning of its life to its end.

Carbonation is a chemical procedure where the carbonic, sodium, and potassium hydroxides in the concrete structure are combined progressively with the carbon dioxide in the atmosphere. The chemical reaction lowers the pH from the 12-11 range to 9-8, reducing its basic environment and allowing oxidation processes to start on the rebars. This reaction's speed is directly related to the porous structure in the concrete and its exposure to the environment. It starts when the element is built and does never finish.

1.4. Research objectives

The paper explores different ways to integrate the durability analysis in the global building assessment analysis performed by private companies and determines some restrictions to adapt. Through developing the tool, the capabilities for BIM to perform building assessments are proven and shown. Two case studies show how the developed tool works inside a BIM environment by analyzing two different structural elements for a residential building.

2. METHODOLOGY

2.1. Integration of the tool in the professional workflow

The tool presented in this article is designed to be for professional use. Several restrictions come from this premise. For this reason, the tool has been designed to work inside the usual workflow followed by private companies when studying a building. Private companies usually have different methodologies and are reluctant to incorporate new procedures. Professionals must understand the workflow and methodologies followed by professionals to develop the tool properly.

After a survey among professionals and personal experience in private business, the authors have divided the workflow into different steps, as shown in Fig 1. First, the building's owners contact the professional and inform them of their needs and problems. From there,

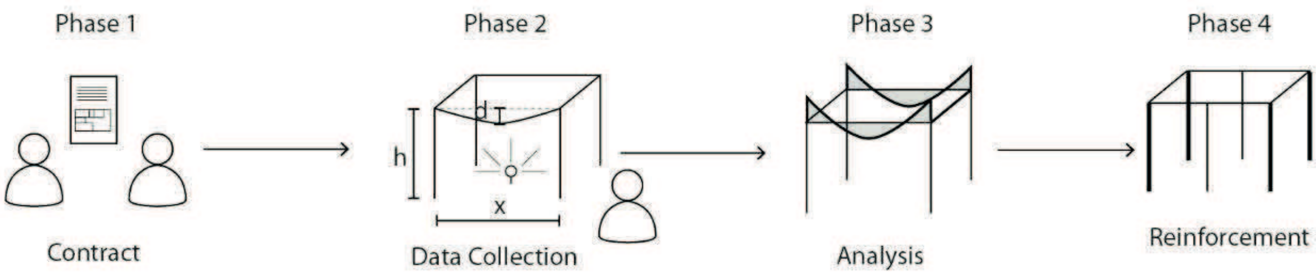
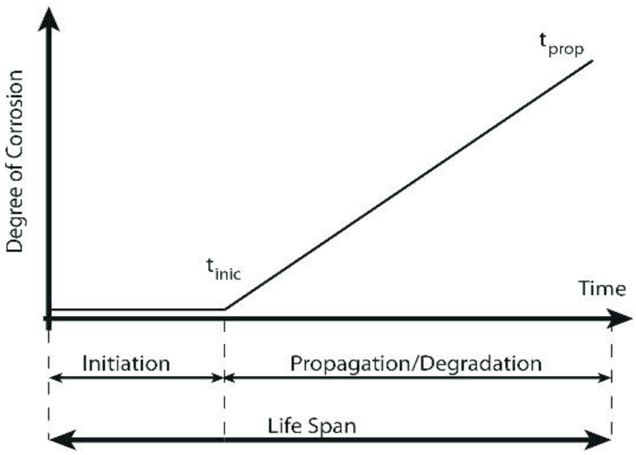


Figure 1. Workflow of building renovation

the professional performs an inspection by visiting the building and collecting the correct data. This initiates the analysis phase when technical solutions are proposed to fulfill the owners' demands. Finally, after the changes have been determined, the changes are built, and the refurbishment is done. This workflow describes the general methodology followed by private firms to perform rehabilitation. During the data collection phase and its posterior analysis, new demands may arise depending on the service life of the building.
The data collection proves itself a critical phase. At this point in the process, it is the professional who determines the building's necessities and state of preservation. Despite the owners' demands, pathologies and preservation problems during this inspection may prove more urgent to preserve the building's service life. Despite its importance, most of these inspections are performed visually by professionals, collecting data directly without performing experiments, limiting the data collected. The limitation in the data collected is a barrier to performing service life analysis. This limits the accuracy of the analysis and needs to be directly assessed when designing the tool.

2.2. Determination of the carbonation depth

The new Spanish structural code “*Real Decreto 470/2021: Código Estructural*” (Ministerio de Fomento, 2021) presents a model to determine the carbonation depth of concrete of a certain age. This method is also presented in other European codes similarly, such as the Eurocodes, without any difference. This model defines the "Durability Limit State" as the regulation states it, one of the Service Limit States that a professional must guarantee in the structure.
Carbonation is a slow degradation process that affects concrete elements reducing their service life. Different degradation processes detriment the elements’ serviceability faster than carbonation, but they depend on the environment and maintenance. Carbonation is the only process in which it is always present, but it is not always the most prevalent. In general, carbonation is the primary degradation in structural elements (beams, supports, or any kind) which are subject to environments with constant humidity and further away from chloride exposures (from natural or chemical sources). These environments are defined as “XC” in the Spanish building codes, following the European building code nomenclature. The carbonation model is based upon Tutti’s model (Tuutti, 1982). It obtains the amount of time a specific concrete element takes to reach a certain carbonation depth. If the carbonation depth is higher than the concrete cover, the element is marked as "carbonated," which means that its rebars are exposed. Oxidation processes start to happen, reducing the element’s service life.



$$(a) \qquad t_{inic} = \left(\frac{c}{k_{ap,carb}}\right)^2 \to\to k_{ap,carb} = c_{env} \cdot c_{air} \cdot a(f_{ck} + 8)^b$$

$$(b) \qquad t_{prop} = \frac{80 \cdot c}{\text{Ø} \cdot v_{corr}}$$

Figure 2. Tutti'scorrosion model (a) Time to initiate the process (b) Propagation time

As shown in Figure 2, the model is composed of two phases. First, the carbon dioxide penetrates gradually into the concrete element, carbonating it constantly. The time necessary for the process to reach the rebar is obtained from Equation 1 (a) and depends on the rebar cover, type of cement used for the concrete, air inside the concrete mass, and degree of exposure of the element. After the element is carbonated, the rebar starts to deteriorate, losing tensile strength and increasing in volume, thus breaking the concrete. Later, a crack will appear on the element's surface, indicating the damage.

To study if an element is carbonated or not is crucial to define its remaining life span and so determine if it requires maintenance or rehabilitation. Following the code's requirement, the limit carbonation depth equals the cover. From there on, the element may need maintenance and further study from the professional. Equations 2 (b) show the time for a rebar to loss enough section to be critically damaged.

2.3. BIM Integration

BIM model work as a database for the professionals where they can share and store different parameters and data from several sources and can define new ones up to their needs. There are several BIM software in the commercial market. In this paper, Autodesk Revit has been chosen. It provides an open-source API for programmers and professionals to work on and is one of the widest adopted BIM software in the AEC Industry. The integration is performed using the API, which uses the C# programming language. Through the API, data is extracted from the model and complemented with input from the user.

As presented to perform the evaluation, specific parameters must be defined on the model to store the data in the right way. Autodesk Revit provides several ways to define the parameters needed to perform this task. The tool presented in this article is a complementary tool that helps professionals who need to work on BIM models despite its setup. Revit's *Shared Parameters* are ideal to achieve this task, as they define parameters that can be added to different elements across different files. Using these parameters, the data can be stored without stopping the professional from customizing its structural element to its needs while performing the analysis.

2.4. Workflow of the analysis and user Interaction

The BIM model is used as a database for data parameters and results to perform the durability analysis. Within this consideration, we can divide the analysis into a three-phase step process, as shown in Figure 3. The first phase is modeling. This step introduces the data from the existing building into the BIM environment. The BIM model is developed in this step and covers every aspect necessary for the building's renovation, such as measurement and materials. Once the model is finished, and the desired Level of Development is achieved starts, the second phase. The data is extracted from the BIM model, and the tool is initiated in this step. The user introduces the remaining parameters and performs the analysis obtaining the results. Finally, after confirming the results, they are introduced automatically in the model and stored as values inside the studied elements.

Several factors, such as environmental exposure and cement type, may be challenging to determine and may vary from element to element. Even though the data is extracted from the BIM model, the parameters can be edited by the user. This additional step does not add complexity to the analysis. It deals with the Black Box Effect (Fernández-Mora, 2018) as the professional receives feedback from the input and knows how much the result varies depending on those parameters.

The tool outputs two different results necessary to understand the remaining service life for the element. One of the results is the time until the element is carbonated, and the second is the evaluation of the carbonation itself. With these results, the professionals should decide if the remaining service life is enough for its purpose.

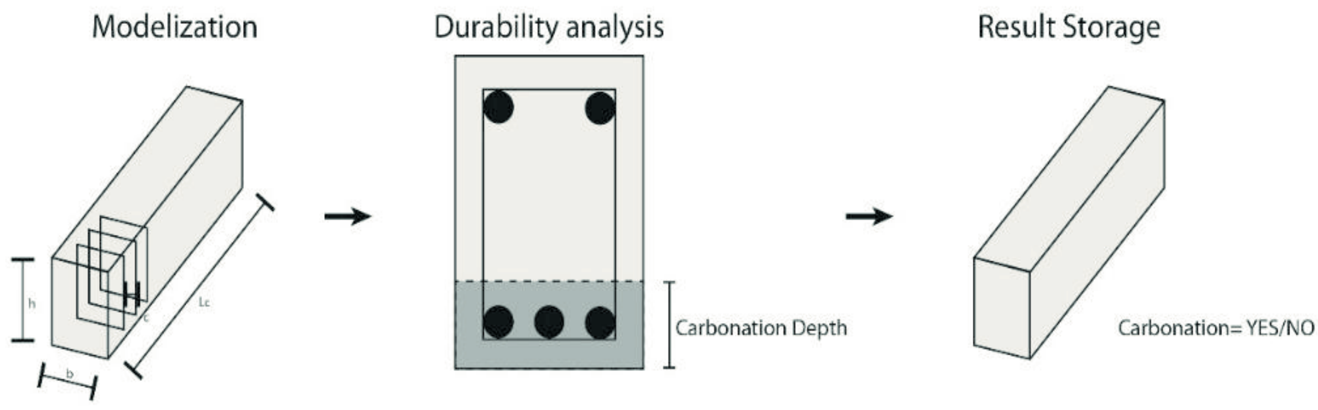


Figure 3. Steps for the durability analysis

3. DISCUSSION AND RESULTS

3.1. Parameter definition and reference values

Several parameters are needed for the durability analysis following the Spanish Structural Code and the posterior evaluation of the carbonation depth. These parameters are stored in the BIM model before the analysis and extracted from there by the developed plug-in. The values for these parameters will be user input and need to reflect the reality accurately to reflect the data. Table 1 summarizes the parameters needed for the analysis.

Visual observation of the element by the professional is not enough to obtain some of the values for the carbonation analysis. While some parameters may be directly measured, some others can only be estimated with indirect measurements or obtained from a laboratory. This section presents an indirect estimation for these parameters, and their

Table of parameters	
Parameter	Unit
Input parameters	
Cover (c)	Millimeters
Concrete tensile strength (f_{ck})	Newton per square millimeter
Environmental exposure (c_{env})	Adimensional
Occluded air (c_{air})	Adimensional
Type of cement	Adimensional
Building's age	Year
Result parameters	
Carbonation depth	Millimeters
Service life left before carbonation	Year
Carbonation	Yes/No

Table 1. Parameters for durability analysis

different values are presented in Table 2. These parameters are: cover, tensile strength, percentage of occluded air in the concrete, and conglomerate composition.

The values provided in the table may be used as a reference by the professional and must be replaced with values obtained through experimentation if available.

Building codes and practices evolve over the years, but they usually are static for some time. Requirements for the materials change and vary depending on and related to industry demands and technology. Considering the building's year of construction, the building code in that year, and the technology available, they can be estimated. The values provided in this section are only valid for the Spanish housing market and may not be accurate for other cases. The natural degradation of material properties during the years has also been considered. These values have been defined after requirements in the different building codes in Spanish history.

3.2. Model visualization and analysis implementation through Autodesk Revit

3.2.1. Revit Family definition

In Autodesk Revit, every building element is an *instance*, and every object is defined by its parameters. A group of *instances* can share properties or describe similar elements, called a *family*. Each parameter value can be exclusive to the instance or can be shared across the same *family*. This categorization describes the relations among any object in the BIM model. The users must define families and their instances corresponding to their necessities.

In a BIM model, there are different *families* to represent a beam, a wall, or a column, and the professional may need to introduce different data onto them. As durability affects every concrete element and the analysis performed is the same, the tool presented can work regardless of the analyzed structural element.

Access to the desired data for the analysis is accomplished using *Shared Parameters*. This type of parameters is defined outside the modeling space and can then be assigned to any element. With this design, the tool is not restricted to a *family* for each element, and the user may implement the data in any structural object in Revit's model. This decision gives flexibility to the analysis as each parameter can be assigned as an *instance* or as a *family* parameter depending on its necessities. They can even be combined with other desired parameters for other purposes outside the analysis.

Reference values					
Parameter	Year of Construction				
	Before 1973	1974-1982	1982-1998	1998-2008	After 2008
Cover (c)	<10 mm.	15 mm.	20 mm.	25-30 mm.	35 mm.
Concrete tensile strength (f_{ck})	10 N/mm^2	15 N/mm^2	15 N/mm^2	20 N/mm^2	25 N/mm^2
Occluded air (c_{air})	>4.5%	>4.5%	>4.5%	<4.5%	<4.5%
Type of cement	Portland cement	Portland cement	Portland cement	Portland cement + additions	Portland cement + additions

Table 2. Reference values

3.2.2. View filters

Once the results are stored in the BIM model, they can be used and managed for different purposes. The results from the analysis are stored on the elements instance so the professional can check them later. Using Autodesk Revit, the data can be represented graphically on the model utilizing View Filters. These graphical filters customize how the data is shown in the 3D model and allow the professional to visualize the elements as desired.

A view filter has been created using the data stored in the Carbonation parameter, which only is applied to analyzed elements. This filter shows non-carbonated parameters as green, carbonated elements as red, and leaves non-analyzed elements unaffected. Using the filter, a choropleth map showing the carbonation in the different elements of the building is created visually representing and summarizing the analysis.

3.3. Case study

Two study cases are developed using the durability analysis tool to determine the carbonation of depth of different structural elements on the same theoretical building. Two case studies are shown, on the same residential building. The sample building is a corridor housing building 32 years old, built in 1990. To simplify the case study, a sole dwelling has been modeled inside BIM. The dwelling is situated on the third floor of the building, which is in the middle of the city and not affected by other degradation processes. The selected elements and the dwelling's distribution are shown in Fig. 4.

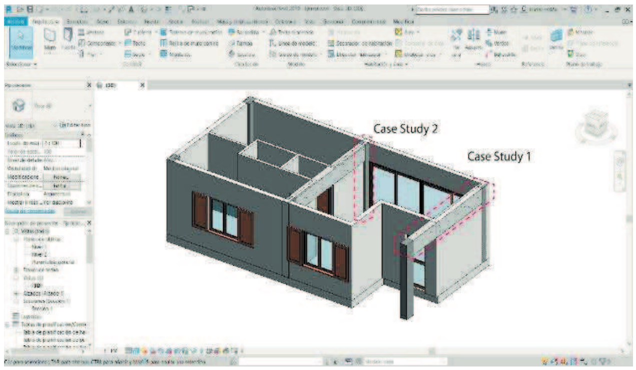


Figure 4. Case studies (1) beam (2) support

3.3.1. Case Study 1: Beam

Element one is a concrete beam partially on the exterior corridor of the housing. The analysis does not differentiate different environments for the same element, so the worst exposure has been selected. The analysis is performed after introducing the data into the BIM model.

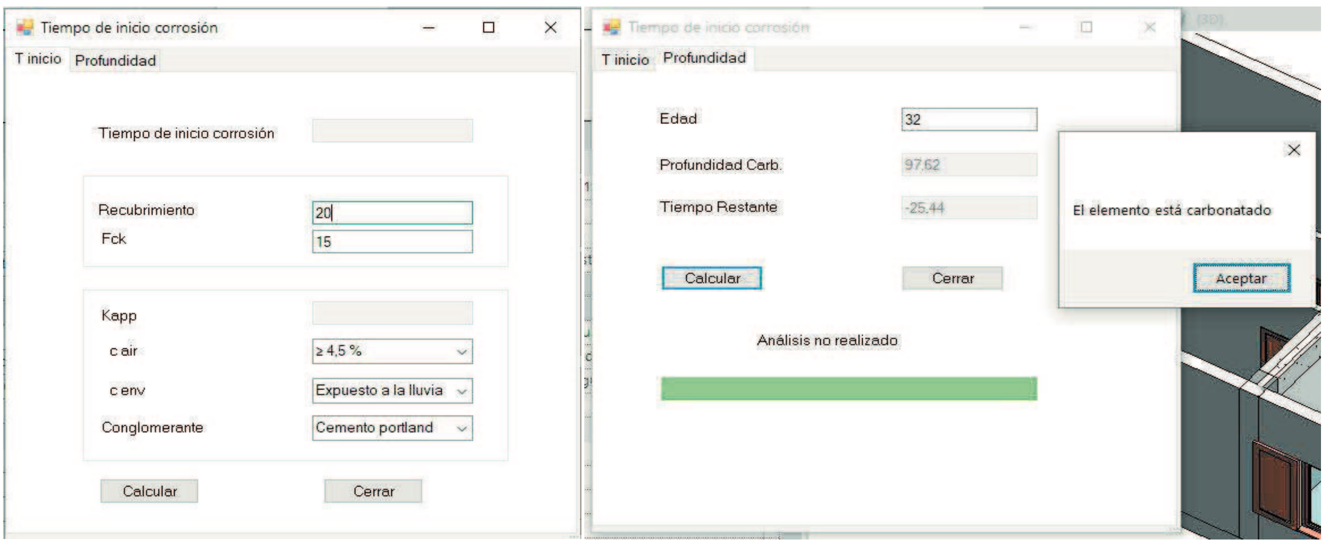


Figure 5. Case study 1 data and analysis

The data is extracted from the instance of the beam in Revit and shown in the plug-in. In the window, the values can be consulted and edited by the user before performing the analysis. When verified, the first phase of the analysis is performed, obtaining the carbonation depth. To perform the second phase, the age of the building is introduced by the user. In this case study, the studied element is carbonated, and the plug-in informs the user with a pop-up.

3.3.2. Case Study 2: Support

Element two is concrete support inside the house. The concrete considered has a higher resistance, as it is more compact, and a test has been performed on other support to measure the cover correctly. To demonstrate the capabilities of the tool the age considered for this element is 5 years old. The element is less exposed to degradation processes than in the previous example inside the house.

The process is analog to the previous one with the data extracted from the model. In this example, the element is not carbonated, and the plug-in informs the professional of the remaining service life for the element.

The degradation process is shown on a progress bar to evaluate the remaining time. After analyzing both elements, the results are stored on the BIM model. The results can be consulted at any given time by the professional. In Fig. 7, the view filter is active, and the professional can track the result for each element based on the color.

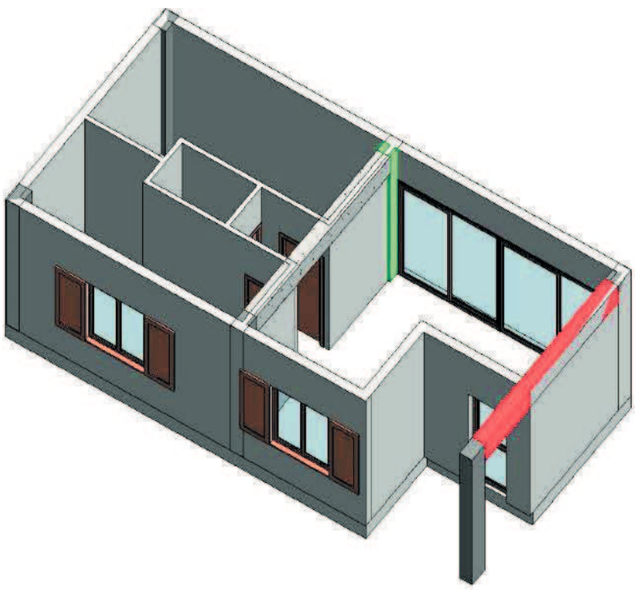


Figure 7. BIM model with view filters after the analysis

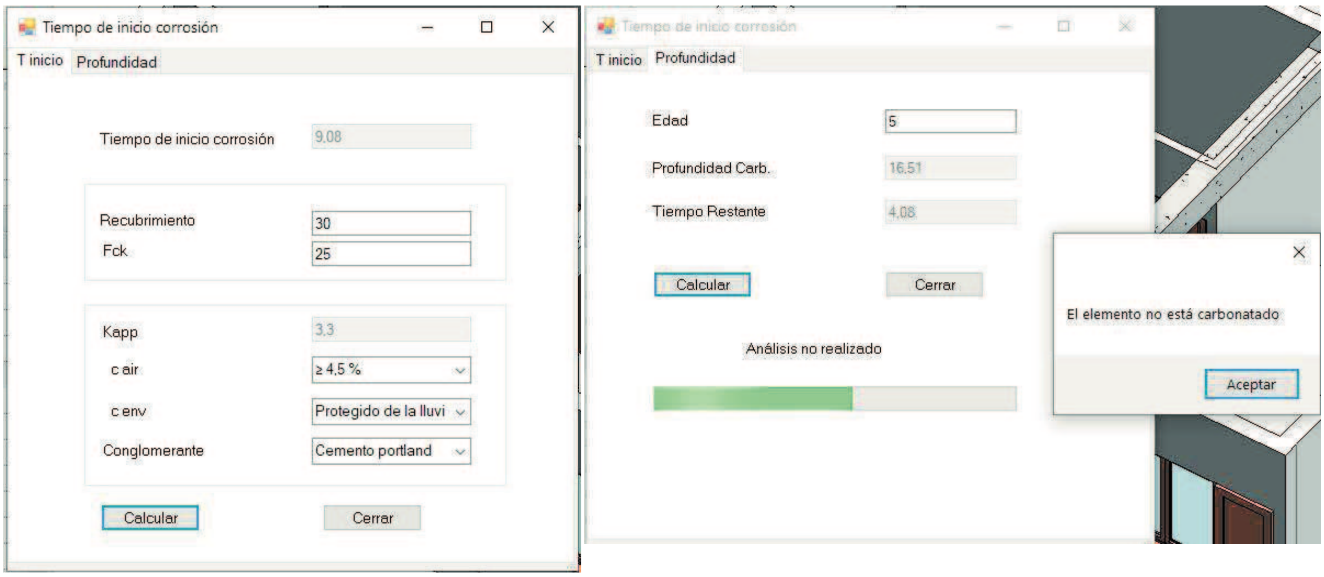


Figure 6. Case study 2 data and analysis

4. CONCLUSIONS

4.1. General Remarks

This paper presents and explores BIM capabilities to manage building degradation analysis for building restoration. This response to a demand in the Spanish housing market and the AEC Industry to restore and rehabilitate buildings and increase their service life. It also is an excellent contribution to sustainability and reduction of CO_2 emissions.

A tool able to evaluate the carbonation in concrete structural elements inside the BIM environment Autodesk Revit has been fully developed and presented. Furthermore, two case studies have been shown to prove its functionality. The analysis result is then stored on the BIM model for future access. The developed plug-in works for any structural element in Autodesk Revit, performing the Durability Limit State analysis by the Spanish structural code.

4.2. Future Research Lines

In the last years, BIM has proven a valuable tool to improve performance in AEC Industry. BIM environments enrich building performance analysis and can determine the preservation state of a building.

The research in this paper lays a foundation for future research lines. Building restoration responds to social demand for sustainability. In order to fulfill the demand, building assessment is imperative and BIM environments have proven themselves able to perform analysis based on stored data.

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