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THE USE OF FTA TO EVALUATE THE POTENTIAL OF THE BIM PLATFORM IN BUILDING REHABILITATION

O USO DO FTA PARA AVALIAR O POTENCIAL DA PLATAFORMA BIM NA REABILITAÇÃO DE EDIFÍCIO

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Abstract

Several studies recognize the potential of interventions in existing buildings to reduce the consumption of natural resources and the use of *new lands. In the context of sustainable design, the adoption of alternatives to support the integrated design and collaborative work - as Building Information Modeling (BIM) - offers a great potential to identify and propose interventions that implement sustainable practices equally - in new buildings as well as in the rehabilitation of existing ones. A case study was performed on the rehabilitation design process of the headquarters of PETROBRAS, in the city of Rio de Janeiro. The main purpose was to identify the potential of a BIM Platform for the improvement of the environmental performance of the building - one of the exigencies of the rehabilitation process - which had considered the requirements of the AQUA HQE environmental assessment and the Brazilian program of energy efficiency, the PROCEL EDIFICA, as its parameters. However, there was little integration among the design team and the BIM model. This article presents the results of the analysis of a BIM Platform used in the design rehabilitation process of the given building, by using the FTA – the Fault Tree Analysis Method. The results indicate that BIM had not been considered from the beginning and the consequence was the low integration of the design process. BIM functionalities could, in turn, have brought more dynamism and integration to the design management process. Therefore, it is necessary to review the design process, in order to incorporate BIM potentialities since the beginning of the process and allow the collaborative work.*

Keywords: Rehabilitation. Environmental quality. BIM, FTA.

Resumo

Diversos estudos reconhecem o potencial de intervenções em edifícios existentes, visto que reduzem o consumo de recursos naturais e de novas áreas. No âmbito do desenvolvimento de projetos sustentáveis, a adoção de ferramentas que auxiliem o projeto integrado e trabalho colaborativo, como a plataforma BIM (*Building Information Modeling*), tem grande potencial para a identificação e proposição de intervenções sustentáveis, tanto em novas construções como em existentes. Um estudo de caso foi realizado sobre o processo de projeto de reabilitação da sede da PETROBRAS, na cidade do Rio de Janeiro. O principal objetivo foi identificar o potencial da plataforma BIM na melhoria do desempenho ambiental do edifício – uma das exigências do processo de reabilitação - que considerou como parâmetros os requisitos do sistema de avaliação ambiental AQUA HQE e o Programa Brasileiro de Eficiência Energética PROCEL EDIFICA. Entretanto, houve pouca integração da equipe de projeto através do modelo BIM. Esse artigo apresenta a análise da adoção da Plataforma BIM no projeto de reabilitação do edifício, através do método da Análise de Árvore de Falhas (AAF). Os resultados indicam que o BIM não foi considerado desde o início e a consequência foi a pouca integração do processo de projeto. Entende-se que as funcionalidades do BIM poderiam ter trazido mais dinamismo e integração à gestão do processo de projeto. Portanto, é necessário rever o processo de projeto para incorporar as potencialidades do BIM desde o início do processo, permitindo o trabalho colaborativo.

Palavras-chave: Reabilitação. Qualidade Ambiental. BIM, FTA.

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Introduction

The 1990s are recognized by the increase in the discussions about the alternatives to be adopted in the incorporation of sustainability requirements to the design of buildings and cities, as well, as the spread of different certification systems for "green" constructions. Aiming to meet these requirements, discussions regarding the design management process have arisen. The main purpose was to incorporate alternatives for the high quality environmental performance of buildings from the design conceptual phase.

However, the rehabilitation of existing buildings should be equally considered in parallel with the production of new ones. In this sense, it is necessary to search for design solutions that can meet the environmental requirements established by the new standards of sustainability, even for existing buildings. Furthermore, the rehabilitation of buildings enables the extension of the buildings life cycle, through the improvement of energy performance and comfort conditions for occupants.

The concern with the high environmental quality of buildings awakened the interest of companies that began to invest in the rehabilitation of their facilities, in order to adjust according to the new scenario, adopting the search for a "green building" also as a marketing strategy.

However, the adoption of these requirements for existing buildings revealed a new challenge: the need to create a database that enables the maintenance of the environmental requirements throughout the life cycle of the building.

As an ally in this process, BIM (Building Information Modeling) arises as an alternative which, among many possibilities, allows the association of geometrical attributes of buildings with the performance entries (thermal, acoustic, and luminal) and data planning, as well as building maintenance programming.

Thus, this paper presents a case study where a BIM based system (Revit) was used for the rehabilitation of an existing building, aiming to facilitate the design management process and the inclusion of the requirements of the AQUA HQE environmental certification, as well as the PROCEL EDIFICA requirements.

Design management with high environmental quality

The design management of a building refers to the process of organizing all phases of development, coordination, and execution of a design activity with the goal of constructing a building. In this sense, the quality of the design process depends on management procedures that facilitate the planning and development of the design activities. Thereby, it is understood that a multidisciplinary approach, interaction, transparency and control of the entire process are aspects that should be considered in the design management process.

Sequential traditional method

The traditional method for design management stands out because of its sequential and hierarchical approach to the process. In a hierarchical organization, the parts of the process flow are better controlled than the whole. Therefore, this flux tends to focus on each activity individually and does not allow the integration among all specialties that concur in building´s design.

The sequential view does not consider the whole process as the focus of control, handling all the activities of the process equally. Thus, the best options for the following step and the interactions between them are not verified (KOSKELA, 1992, 2007; CLAUSING, 1994; MELHADO, 1999; FABRICIO, 2002; KHALFAN; RAJA, 2005).

Therefore, it is important to emphasize that the development of the design in the sequential method creates fragmentation, as it does not treat the process as a whole and assumes that each part is contained in itself. Thereby, not everyone involved has access to all the exchanged, prepared and stored information throughout the process.

Contemporary method

The increasing complexity of buildings has pointed the need to design in an integrated manner in order to improve information sharing and communication between the parties involved (DEUTSCH, 2011). Thus, it could be highlighted that the integrated management of the design documents, data and information contributes to the transparency of the design process.

This new strategy of integrated management can be identified as a "contemporary method", since it involves characteristics of the collaborative, concurrent and integrated methods.

While, the collaborative method requires a process that integrates the design team through collaboration, communication and coordination, the concurrent method is more focused on the process, because, all disciplines of design are develop at the same time, which means simultaneity of activities and tasks. Therefore, the generation of information occurs simultaneously, but not necessarily, in a collaboratively and integrated manner. On the other hand, the integrated method, although very close to the simultaneous method, is more focused on the outcome and on the integration of the product and the process information, on the aspects of the life cycle of the enterprise and on the solutions through a continuous workflow, which does not necessarily mean that there is simultaneity (DEUTSCH, 2011; KAMARA; ANUMBA; CUTTING-DECELLE, 2007; KOSKELA, 2007; FABRICIO, 2002).

In this context, BIM can support the communication between team members and contribute in making the exchange of information more efficient (KAMARA; ANUMBA; CUTTING-DECELLE, 2007; CORRÊA, 2010; BEBER; SCHEER; WILLE, 2007; OLIN; JYLHA; JUNNILA, 2012).

BIM and sustainable design

BIM can be an anticipation of the reality that deals with developing a set of representations (models) of the construction information.

According to Williams (2013), BIM is a targeted approach for obtaining and harnessing information throughout the design process. Deutsch (2011) describes BIM as a software set and also a process that is used to produce and manage constructive data through the building life cycle. This "digital toolkit" allows to design and to virtually build the model multiple times, rehearsing and optimizing resources throughout the process design, eliminating possible errors, waste, and inefficiency.

Eastman *et al*. (2011) complemented that with BIM, it is possible to digitally create one or more precise virtual models of the building. These models seek design support throughout their phases, allowing better analysis and control of the processes. When completed, these computer-generated models comprise the precise geometry and data necessary to support the construction, fabrication, and procurement activities through which they are performed.

Thus, a BIM model is built, demanding interoperability within heterogeneous BIM platforms that use and update the model throughout its entire life cycle. In this sense, it is important to highlight the research developed by Olin, Jylha and Junnila (2012), informing of the potential of BIM as a collaborative tool, that can be used for the management of documents and information, for project management, budget control, planning, schedule, environmental simulations and to analyze variables related to feasibility, costs, energy and environmental performance. The authors add that the advantages of BIM are not limited to the conception phases of the design and construction, and they may be useful throughout all the life cycle of the building, such as in maintenance, rehabilitation, analysis of space usage and environmental management, as well as for predicting costs of the operational performance.

Therefore, the implementation of a platform that enables the integration between different design specialties and improves the visualization of data and design information increases the efficiency and quality in construction. It can also stimulate the collaboration between the design team, facilitate the transparency in the workflow, allow the interoperability, and therefore, contribute to the adoption of the contemporary design method.

Buildings with high environmental quality

The architecture of high environmental performance has as its principles: to design and to build with less environmental impact, through the reduction of the use of natural resources, and minimizing the pollution harmful to the environment. Regarding the production of sustainable buildings, Silva, Salgado, and Silva (2015) underline that the information relative to building design has become even more complex with the adoption of environmental performance targets.

Kamara, Anumba, and Cutting-Decelle (2007) and Salgado, Catelet, and Fernandez (2012) affirm that, for the production of buildings with high environmental quality, it is necessary to impose a new method to organize and manage the design process. For this purpose, the improvement of the design process depends on the establishment of a management system that can help the professionals to deal with a large number of requirements related to sustainable buildings and that enables the interoperability between the different design professionals. This method must guide a workflow focused on collaboration, integration, and simultaneity. With this idea, the *contemporary method* could address these requirements since it turns the workflow more dynamic and efficient, promoting the dialogue between the design team members.

In this context, the potential of using a BIM platform for implementing sustainability requirements should be highlighted. De Paula, Uechi, and Melhado (2013) confirm the potentialities of BIM by pointing out that the advance of this technology will help the inclusion of environmental targets and to establish, in the future, standards of excellence. Bloomberg, Buncey, and Resnik (2012) emphasize that the integration and collaboration provided by the use of BIM contributes to a sustainable integrated design process. The authors stress that the benefits of using a single database for the analysis of environmental performance are: to include environmental requirements and to improve communication among the design team.

Therefore, the development of a virtual model with building information enables the interoperability and the inclusion of environmental targets through simulation and environmental analyses. However, it is worth mentioning that the mere use of BIM will not be enough to improve the design management. Its proper use will only be possible through the establishment of a communication system between the design team members, allowing the follow-up of revisions and changes without information duplication or rework.

Environmental Certifications

Environmental certifications are tools that seek to evaluate and measure the environmental performance of buildings. Many countries decided to develop their environment rating system, considering the specificities of the different regions. Reed *et al*. (2009) point out that the systems of assessment of environmental performance promote continuous improvement for building performance, minimize environmental impact and establish reliable standards for objective evaluation.

Only recently, Brazil has given its first steps towards the discussion and the adoption of methodologies that might help the production of buildings with high environmental quality (SILVA; SALGADO; CAMPOS, 2014). Among the methods from abroad, it is possible to highlight the LEED™ North American system (Leadership in Energy and Environmental Design), the French method HQE® adapted to the Brazilian reality into the AQUA HQE process, the British method BREEAM and SBTool developed by iiSBE. The first two methods have been adopted by Brazilians constructors, particularly in the Southeastern region of the country.

The HQE was created in 1996 by the HQE Association (1). The French system has values of standard benchmarks for different types and features (CERTIVEA, 2008). The adaptation of this certification to the Brazilian scenario gave rise, in 2009, to the HQE AQUA process, which is the first technical reference of Brazilian environmental certification. As well as in the French system, the entrepreneur sets the desired environmental performance profile for the project and implements a management system to ensure the achievement of the defined performance (FUNDAÇÃO VANZOLINI, 2012).

The method is based on environmental targets grouped into four categories: eco-construction, eco-management, comfort and health, which unfold into 14 performance targets that must be analyzed to define the profile of the Environmental Quality of the Building (QAE). To obtain the certification at least three targets must be achieved with excellency and a maximum of seven targets should be accomplished at a "basic level." The remnant targets should be attended as “superior” level.

It is important to emphasize the role of the environmental certifications, regardless of the preference provided by stakeholders. It is understood that the main merit of proposals is in helping architects and engineers to re-think the design process, aiming at the incorporation of solutions that may positively contribute to the environmental quality of the building.

Research strategy

This study refers to the production of buildings with high environmental performance, from the management perspective of their design process. The definition of the objective of the research, as a holistic and an interpretive approach to the design process, resulted in an empirical research to investigate a contemporary phenomenon in its real context. Thus, the research approach combines a qualitative strategy with the case study (GROAT; WANG, 2013).

The theoretical background consisted of bibliography review of the themes, such as the design management, sustainability, and intervention in existing buildings.

The case study is a corporate building – the PETROBRAS’ headquarters in the city of Rio de Janeiro, - known by the acronym EDISE. One of the primary goals of the rehabilitation was the incorporation of environmental performance parameters (AQUA HQE ® environmental rating system) and energy efficiency requirements (Procel label – level A); with the design team having adopted a BIM Platform.

For the case study, the data survey considered the analyses of design, documents, drawings, calculation memories, reports, contracts, memorials, flowcharts, technical specifications and focused observation. It is also important to mention the participation of one of the authors, as a member of the design team, which allowed the attendance to design review meetings, among others opportunities.

The participation of the development of the rehabilitation design process has guided the data collection of the case study. The following strategies stand out:

- researcher's involvement in the design review meetings;
- examination of the registers of the design coordination, such as minutes of meetings, reports of the progress of the design, among others;
- participation in the lectures for the presentation of the BIM model by the external contracted company;
- supervision of design documents;
- oversight of the AQUA HQE rating system and the PROCEL energy efficiency label reports and documentation.

The research has been carried out considering the following steps:

- identify the environmental quality profile defined for the rehabilitation of the building;
- follow the modeling process of the existing building using the BIM platform (the modeling process

involved laser scanning with the use of drones associated with photogrammetry);

- evaluate if the BIM model helped architects in the definition of the design solutions required to meet the environmental targets;
- identify the problems related to the coordination of the design process using the BIM Platform, aiming at environmental quality.

The Fault Tree Analysis Method (FTA) was used to analyze the problems related to the case study. The observation of the design management process of the case study combined with the theoretical basis of the literature review constituted the method used to identify the design problems. The data obtained were exposed through the construction of a fault tree for undesired events.

The research data were then synthesized and compared with others inquiries and the literature review. The results of the analysis supported the conclusions and recommendations.

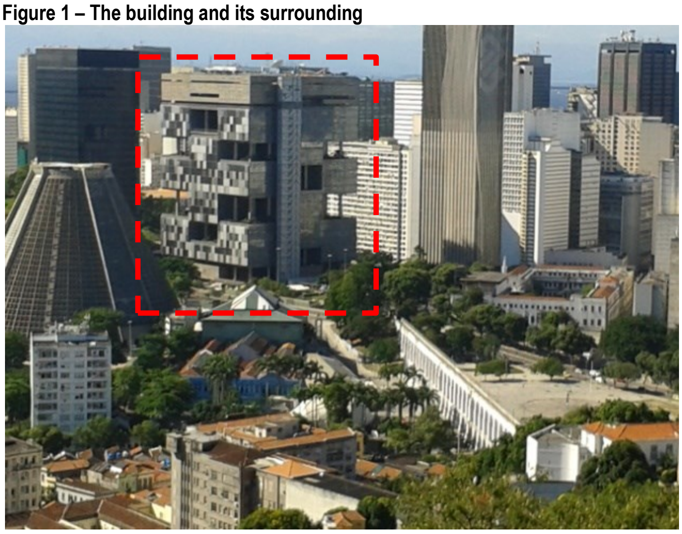
Case study

This case study was carried to characterize the use of a BIM Platform in a rehabilitation of a building for the improvement of its environmental quality.

The original design

The original design of the building that lodges the company was chosen using a competitive bidding process, organized by the corporation, through the Institute of Architects of Brazil (IAB-RJ), in 1967. The building conception includes precepts of bioclimatic architecture, following the main requirements defined in the official announcement: the maximum occupation of the land with minimum vertical circulation; the valorization of the social contact in pleasant environments and the desire of becoming a landmark in the city's architecture, highlighting its landscape integrated the surrounding (PETROBRAS, 2008; GUASTI, 2008; SANTOS; ZEIN, 2009).

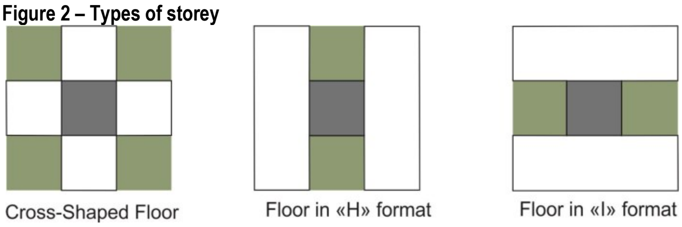
Figure 1 – The building and its surrounding



Source: Authors (2014)

The team selected, headed by the architecture office Forte-Gandolffi Associates, idealized a building divided into: an underground, a framework (ground floor, 1st, and 2nd floors), a body-building (3rd to 22nd floors) and a crown (23th to 26th floors). The central module shelters the vertical circulation and the services (restrooms, emergency stairways, power distribution pipes and telephony, besides the elevators shaft); being this the only cluster which is repeated on all floors of the building.

Figure 2 – Types of storey



Source: SILVA; SALGADO; CAMPOS (2014)

The great box released by 17 empty spaces is produced by the nesting of floorplans with "Cross," "H" and "I" shapes (Figure 2). The roof houses a garden with Burle Marx´s landscaping (PETROBRAS, 2008; GUASTI, 2008).

Around 2008, the 6th floor was totally remodeled. This floor was chosen because of its "I" format (Figure 2) which presented the largest built area compared to other floor formats. Thus, the enhancement of this floor oriented the development of the Basic Design for the other floors. The rehabilitation design initiated in 2013, aiming at the adequacy to the current and future needs of the construction.

Process framework of design development

The rehabilitation design was divided into four stages: Conceptual Design, Basic Design, Detailed Design, and Construction. Firstly, the Conceptual and Basic Design Phases were accomplished, using conventional 2D software for the design. The interest to rehabilitate the building to meet the requirements of the AQUA HQE process further justified the production of the model in BIM (SILVA; SALGADO; CAMPOS, 2014).

The employees of the office that were in charge of the design development supervision prepared a document named “3D Modeling Technical Specification”, which was delivered to the contractor for the fulfillment of the Detailed Design.

The original design documents and measurements of the existing building have been used for the construction of the digital model. The method used includes laser scanning with drones associated with photogrammetry. All the rehabilitation design data, such as the renovation of the facilities, the internal layout and shading devices, were inputted in the BIM model.

The development of the Detailed Design phase took place with the construction of a parameterized model, allowing the design team to identify interferences between the different design disciplines that could not be detected in a design developed in 2D.

Design management with BIM

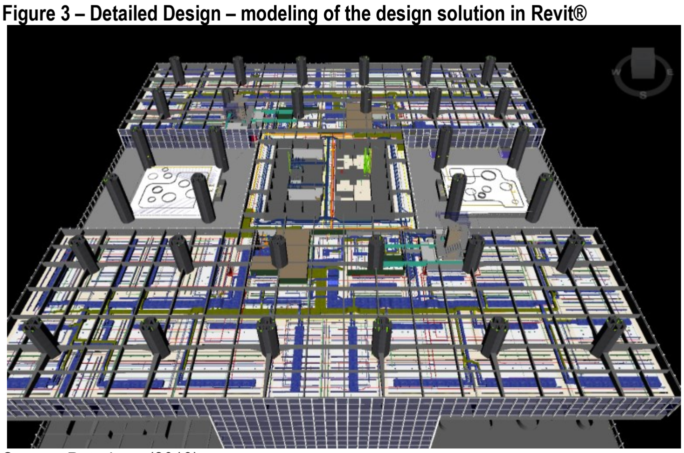
The issuance of daily reports of interferences was the procedure established for checking the interferences and integration between the subject and the contractor. Those reports were grounded in the parameterized model itself, employing “clash-detection” procedures. Later on, those documents were forwarded to the weekly design meeting and reviewed by each leader of the subject involved.

The interdisciplinary compatibilization was carried out through monthly meetings, between the internal project coordinator (member of the contracting company) and three members of the contracted company: the design coordinator, the BIM manager and a team of designers.

For the model management, the inspection team prepared an individual checklist for each discipline involved. Thus, the modeler shaped the element, then checked for interferences. The 3D model had also been used during the review meetings, every two months or according to the necessity of the design team (SILVA; SALGADO; SILVA, 2015).

The approval of the documents by the company was performed using the Project Management System, which allows the documents to be analyzed and commented by the inspection team, before returning to the contractor (design office), which made the necessary changes. Nonetheless, this system has specific internal procedures that demand to receive the document in pdf.

Figure 3 – Detailed Design – modeling of the design solution in Revit®



Source: Petrobras (2013)

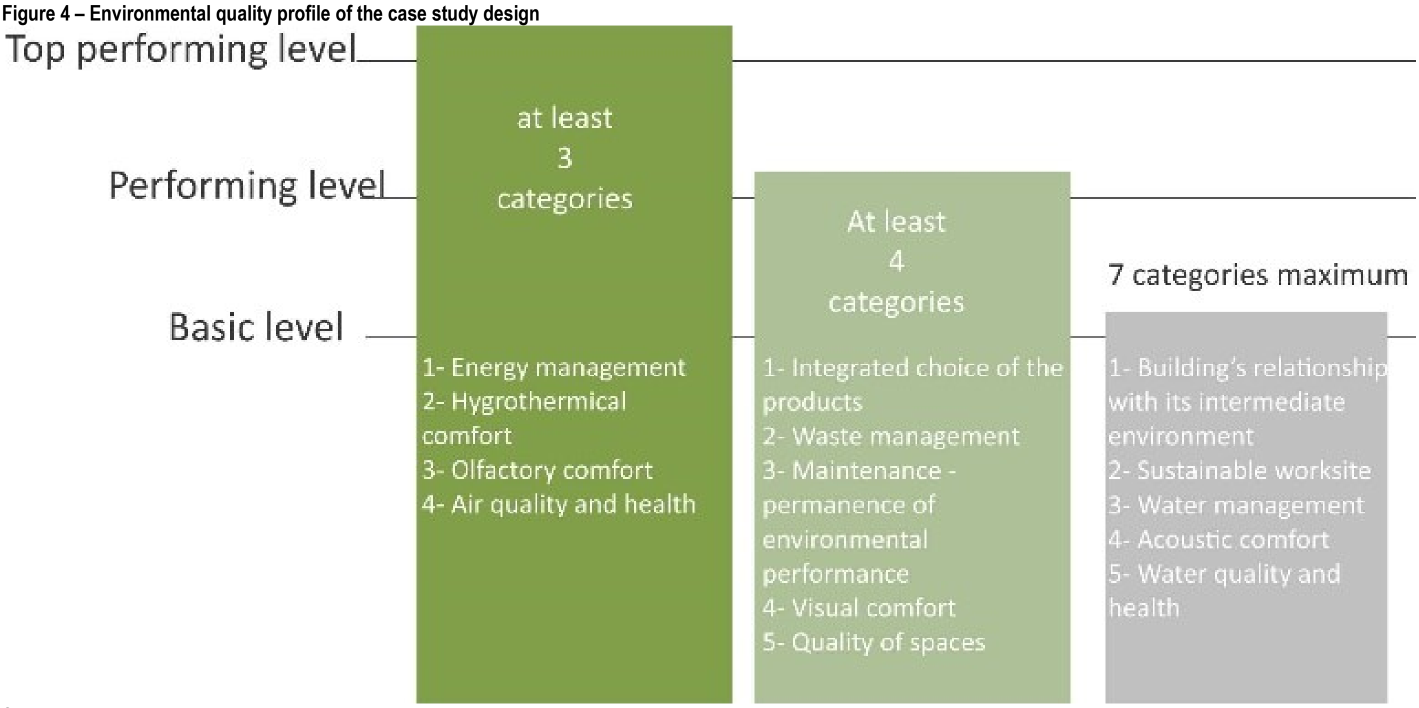
During the design process, although the BIM Platform was used to model the building, it was observed that the validation of the design documents was made through pdf archives. This practice indicates that BIM was not adopted as desired - a platform for an integrative and collaborative design process - but only for the 3D view of specific parts of the project.

One of the main issues that led to the decision of developing a construction BIM model was the possibility of creating a database of the project. The database can be used to operation and maintenance activities of the building as well as the accomplishment of future renovations. However, the model must always be updated.

Sustainability requirements

The scope of the project estimates the inclusion of sustainability solutions with the attainment of Energy-Efficiency Labeling of the “Procel Edifica” Program level A and of an environmental certification. For this purpose, the contractor had to prepare reports, simulations and provide all documentation, information, and records required by the Licensing Authorities. Concerning the environmental certification, an option was made by the AQUA HQE process, in light of its resilience, as the stakeholder must prepare the Environmental Quality Profile (QAE) according to the specificities of the construction. The environmental profile defined for the project was characterized according to Figure 4 and Table 1.

Figure 4 – Environmental quality profile of the case study design



Source: The authors

Table 1: Environmental Profile of the Studied Building

Category	Levels	Measures
Building´s relationship with its immediate environment	Basic	Check the minimum
Integrated choice of the products	Performing	Comply with the Brazilian Standards of Buildings Performance, quality programs and technical assessment. Corresponds to the level of good practices. Materials already regulated
Sustainable worksite	Basic	Perform inventory of residues generated in the scrapping environments
Energy management	Top-performing	Perform calculations aiming at Labeling with the PROCEL Edifica certification
Water management	Basic	Comply with the minimum performance acceptable for a construction of this type. The proof of this criterion would be the use of an equipment to reduce water consumption
Waste management	Performing	Perform inventory about the separation of residues.
Maintenance – permanence of environmental performance	Performing	The automation is already a practice in the company. BIM offers a great potential to operation and maintenance phase.
Hygrothermal comfort	Top-performing	Check through calculations
Acoustic comfort	Basic	Check the minimum servicing acceptable
Visual comfort	Performing	Perform calculations aiming at Labeling with the PROCEL Edifica certification
Olfactory comfort	Top-performing	Comply with criteria, such as type of ventilation, materials with low issuance of volatile organic compound (VOC), exhaust system of the restrooms separated from the system of the offices
Quality of spaces	Performing	Comply with Brazilian Standards of Buildings Performance, quality programs and technical assessment. Corresponds to the level of good practices
Air quality and health	Top-performing	Perform calculations
Water quality and health	Basic	Perform the maintenance programmed in the water supply system

Source: SILVA; SALGADO; CAMPOS (2014)

During the development of the construction project, all the documentation for the certification of the enterprise by the label HQE AQUA and labeling on energy efficiency PROCEL had been prepared.

Regarding the AQUA certification for existing buildings, it is worth adding that there is no need to perform simulations, only the proof by calculations, reports, standards and inventories. In the case study, nevertheless, considering the parametrical modeling, it would have even been possible to perform such simulations (SILVA; SALGADO; CAMPOS, 2014).

Different design solutions have been implemented to improve the building's environmental performance, such as:

a) Reduction of energy consumption: the design was prepared to achieve the level A of the labeling requirements of the Procel. The attendance to the label requirements significantly reduces energy consumption. In addition to the targets of reducing energy consumption, the retrofit of the air conditioning and automation systems are also considered.

b) Integrated choice of materials using certified products, carpets and other low-VOC materials, such as glues, paints, and solvents that do not emit harmful gases to the ozone layer.

c) Reduction of water consumption, with the use of pressure reducers and water saving devices in the consumption points. The use of this equipment attends to the basic level of the AQUA HQE rating system.

d) Improvement of indoor air quality, by using materials with low emission of substances harmful to health in the new layout.

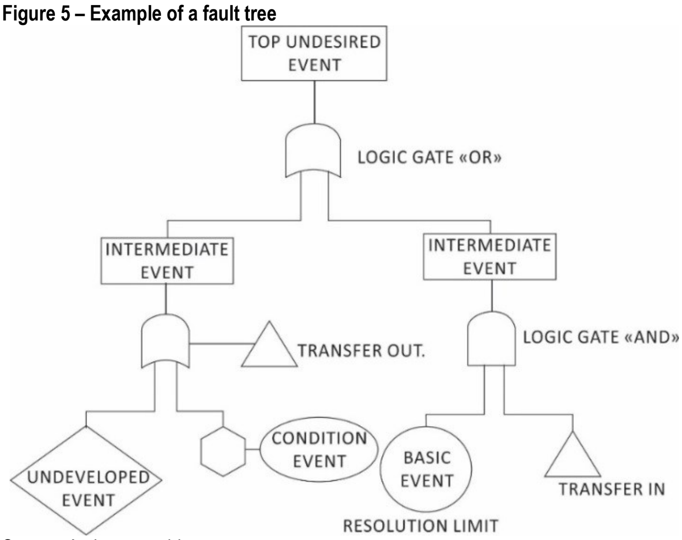
e) The building has a good thermal performance due to the characteristics of its envelope with solar protection devices. In the rehabilitation design, the use of humidity control and an air quality equipment planned to improve thermal comfort. Furthermore, the thermal comfort requirements oriented the new organization of projected spaces.

f) The automation of an air exchange system and the points of external air intake are located far from odor or pollution emitting sources. These design solutions contribute to obtaining the top-performing label on air quality and health.

The use of fault tree analysis

To identify the effectiveness of BIM in the rehabilitation of buildings, aiming at the inclusion of environmental quality requirements, a qualitative analysis of the design development of the case study was made. The method adopted was the Fault Tree Analysis (FTA), known as a technique for problem-solving. The FTA, according to Vesely *et al*. (1981), is a systematic method for information on a system. The proposal is a deductive analysis to resolve an unwanted event, exhaustively searching for the causes of failure, thus clearly showing all the different interfaces that are necessary to reach the top (undesired) event. The method can be used to evaluate a proposed project according to its safety and reliability, as well as to optimize tests and maintenance, quantifying the probability of failures and identifying the weaknesses of a system, the effects of human error and efficient improvements to a system. Figure 5 shows a schematic example with the symbols used for the construction of a fault tree.

Figure 5 – Example of a fault tree



Source: Authors graphic

The FTA method is a top-down thinking, and a fault tree is composed of different symbols that are combined through logic gates. The fault tree construction begins with the identification of a failure, which is the **undesired event** (Figure 5). This event is the result of a combination of failures and is presented through logic gates "AND" or "OR". Then, the fault tree path is defined through failure events that are **intermediate events** acting through logic gates (Figure 5). The **logic gate "AND"** indicates that an output fault occurs if all of the input faults occur. While the **logic gate "OR**" points that an output fault occurs if at least one of the input faults occurs. (SAKURADA, 2001; HELMAN; ANDERY, 1995; VESELY *et al.*, 1981).

The fault tree construction continues until the definition of the **basic event** (Figure 5), which means that the limit of resolution has been reached. However, the causes of some events could not be found. These events are called **undeveloped events** (Figure 5) and they are not further developed because the information is not available or it is not interesting to found out its cause (SAKURADA, 2001).

The FTA was chosen as this method could identify the main problems faced during the design development of the case study. Thus, through the FTA method, it was possible to determine the causes of the undesired events and consequently avoid their recurrence in following projects. Therefore, it brings the possibility to recognize the opportunities for design improvements, based on the lessons learned from the experience of the case study.

For the application of the FTA method, the following authors were used as reference: Ki-Chang *et al.* (2015); Simões Filho (2006); Helman; Andery (1995); Vesely *et al.* (1981) and Oliveira (s.d.). These authors support establishing the sequence of procedures, for the analysis of the undesired events, as described below.

Stage 1: Determination of the top (undesired) event for analysis.

Stage 2: Data and information collection.

Stage 3: Definition of the system, its boundaries, and interfaces.

Stage 4: Detailed analysis of the system.

Stage 5: Fault tree construction.

Stage 6: Survey of the data and faults.

Stage 7: Definition of minimum cuts, review, and validation of the fault tree by checking the procedures adopted.

Stage 8: Qualitative and/or quantitative evaluation of the fault tree.

Stage 9: Analysis of the results obtained.

Stage 10: Conclusions and recommendations.

Stages 1, 2, 3 and 4

The top events were defined based on the literature review (design management, sustainability, and intervention in existing buildings) and the analysis of the design development of the case study, with a focus on the information workflow supported by the BIM platform, in the development of buildings with high environmental quality.

From the analysis of the case study, it was possible to identify some aspects that contributed to the inefficiency of the process, like the following:

a) The decision to use BIM and to certificate the project (AQUA HQE and Procel) was made only in the Detailed Design phase and not in the conceptual phase, as recommended.

b) This was the first experience of the internal design team of the company with BIM.

c) There were some specificities of the internal procedures of the contracting company to manage the design process did not consider the possibilities offered by BIM.

Therefore, the case study analysis identified four top (undesired) events. These events are listed below.

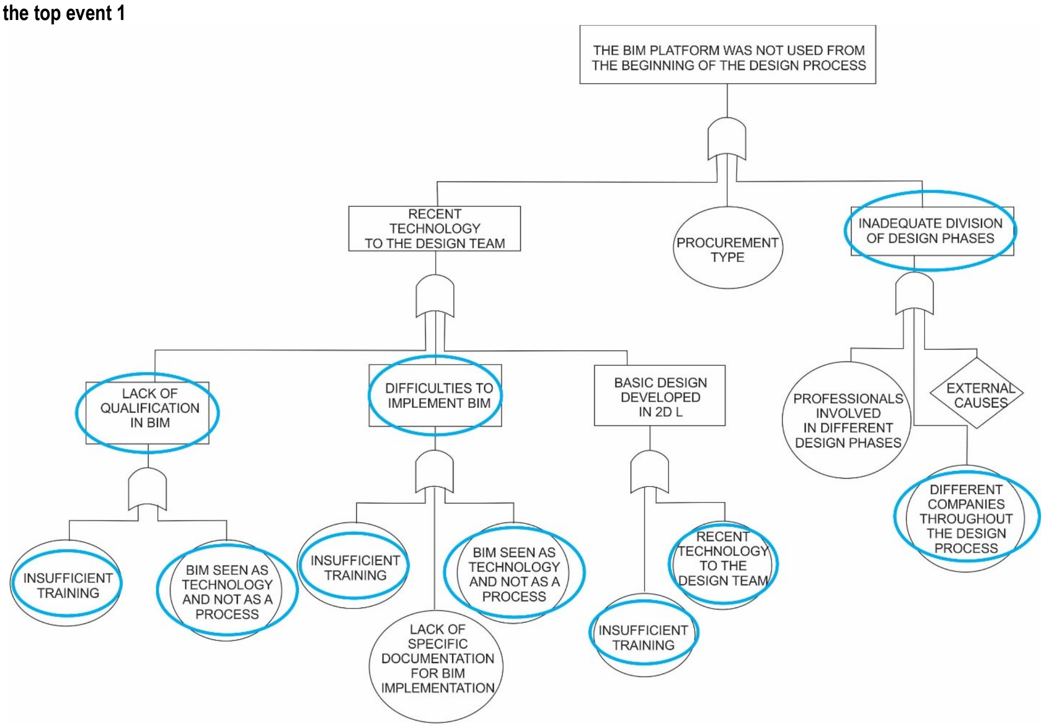
Top event 1: The BIM platform was not used from the beginning of the design process (Figure 6).

Top event 2: The project environmental quality profile was not collaboratively established (Figure 7).

Top event 3: The information exchange was not performed using the BIM Platform, but through traditional methods from the sequential design process (Figure 8).

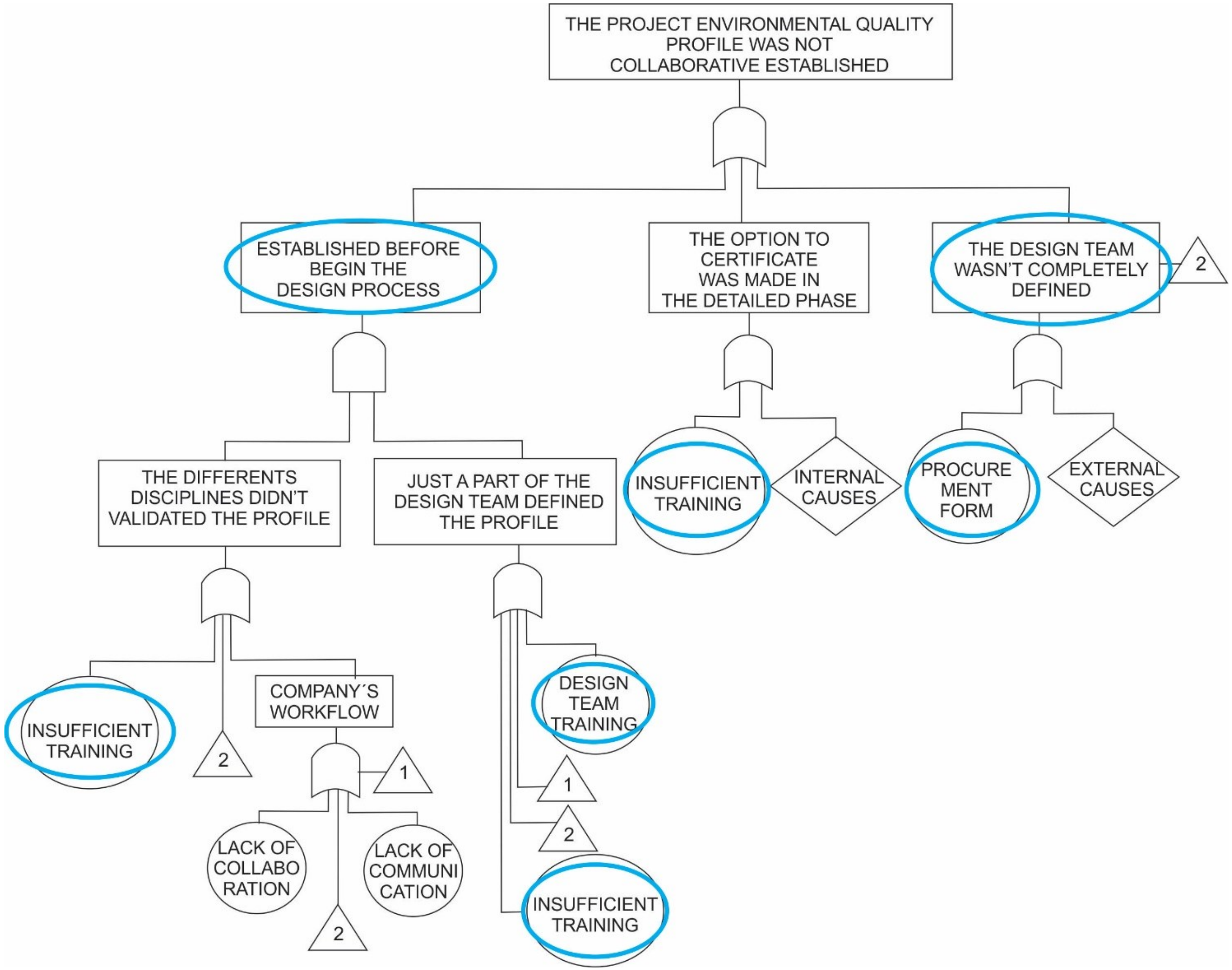
Top event 4: The validation of design solutions and coordination between disciplines did not use the BIM Platform (Figure 9).

Figure 6: Fault tree of the top event 1



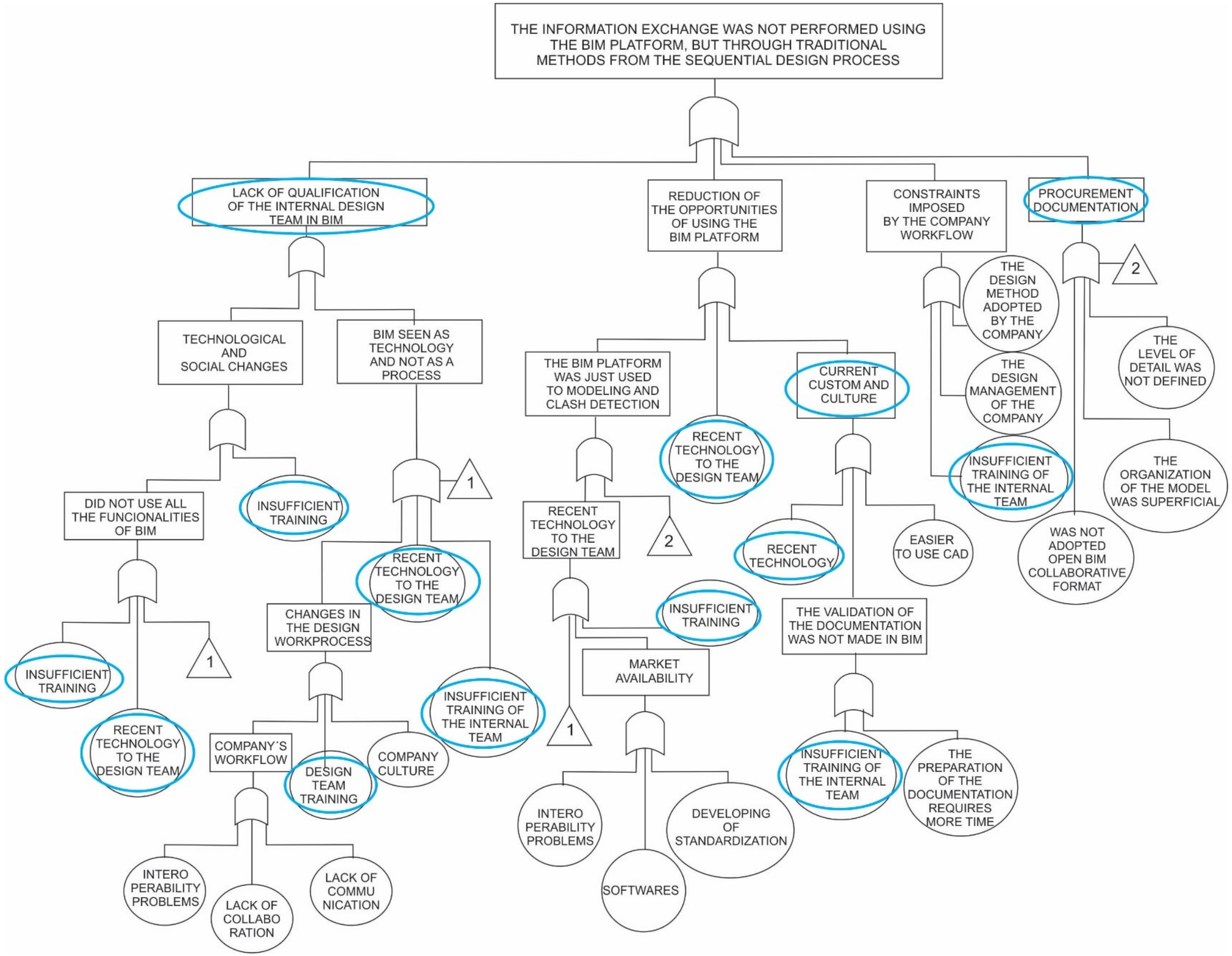
Source: The authors

Figure 7: Fault tree of the top event 2



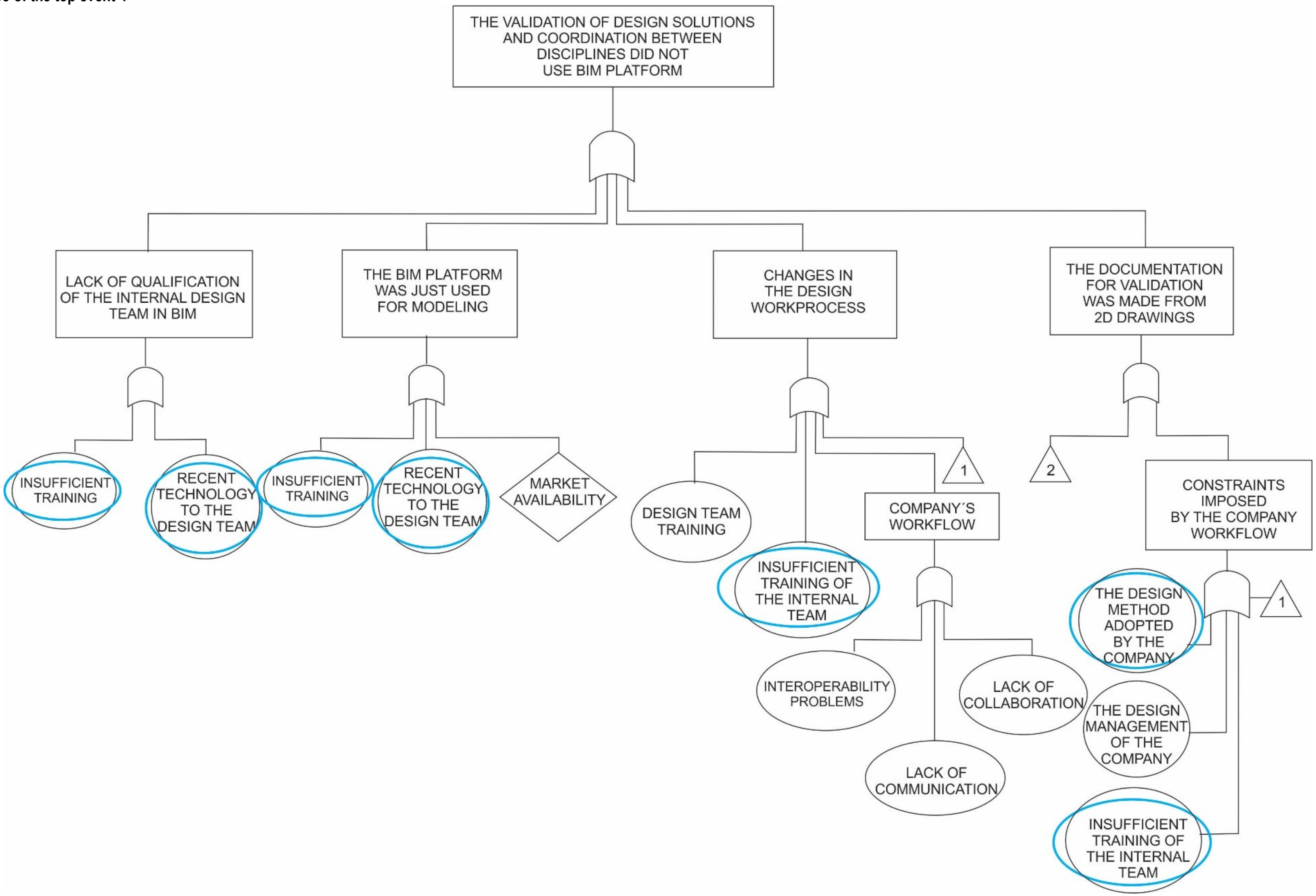
Source: The authors

Figure 8: Fault tree of the top event 3



Source: The authors

Figure 9: Fault tree of the top event 4



Source: The authors

Stages 5 and 6

The fault tree construction was made following a deductive and logical process that began with the unwanted event and finished with the exposure of the causes and failures that resulted in the top event (the FTA solution). The determination of these events continued until the root cause was identified. Therefore, from a bottom-up approach, some of the possible failures were identified.

Stages 7 and 8

The procedure, after the construction of the diagram, was the validation of the fault tree, with the purpose to verify if the proposed objectives were met and if the graphic was described clearly. Thus, the fault tree validation was made by the support provided by the literature review and the observation and analysis of the design development process of the case study. The results obtained guided the decisions, and the recommendations reported.

The evaluation of the FTA method, according to Oliveira (s.d.), can be both qualitative and quantitative. The purpose is to identify combinations of failure events that lead to the top event. In this research, the option for the qualitative analysis was based on the nature of the case studied. The option for a quantitative analysis was not applied because it would require the use of quite complex mathematical expressions far from the scope of this investigation. The validity of a qualitative analysis is pointed out by Lafraia (2001), who indicates that excellent results can be obtained with the application of a qualitative evaluation.

Data review

This section serves to define the corrective actions that could be taken to prevent that the top events re-occur. Although the results obtained in this specific case study cannot define general strategies, some aspects are, common to all design management processes that intend to use a BIM Platform. The application of the FTA on the case study has revealed the following three aspects to be considered in the design buildings with high environmental quality, using a BIM Platform.

Environmental targets

The procurement documentation defined that the hired design office should have adapted the solutions proposed in the Basic Design to the environmental quality profile established by the company design team. Hence, the project should have been able to obtain the HQE AQUA certification. However, the FTA highlighted that the BIM Platform was not used to meet the environmental targets of the design. Three reasons were observed: it was not defined in the procurement documentation, the company design team did not use BIM full potential for designing with high environmental quality, and the implementation of the BIM platform had a technology emphasis instead of a process emphasis resulting in a partial use of its functionalities.

Insufficient training:

The knowledge of the Revit® software was one of the criteria for contracting the design office who developed the Detailed Design. However, neither the professionals of the contracting company (internally responsible for monitoring the design development) nor the hired design office were trained, or knew of the potentialities of the BIM Platform. Thus, to overcome this obstacle, the contracting team scheduled Design Review meetings with the presence of all the design professionals (contracting company and contracted design office). The insufficient training of both teams (internal and external) resulted in repetitive procedures and unproductive activities to verify the design documents and share the information between the design team members.

The working method used by the design team

One of the consequences of the lack of knowledge of the BIM Platform combined with the internal operating procedures of design management was the repetition of unnecessary tasks. An example of repetitive work was that all design checks occurred in documents presented in a pdf format, with this information being later updated to digital documents. Instead, the checking procedures could have been made in digital documents associated with the digital model.

The Design Review meetings were a positive aspect. They contributed to the collaboration of the design team, since they promoted the analysis of the model in a multidisciplinary manner.

The FTA analysis indicates that the workflow adopted by the company should have been more flexible, regarding the type of formats for the exchange of information and files.

In this sense, the FTA method contributed to diagnose failures and identify the basic events, such as insufficient training, procurement type and internal procedures for design development.

The basic events suggested that the majority of them refer to issues related to the management of the design process. They can be divided into social impacts (workflow, company's culture, teamwork, and communication) and technological impacts (interoperability, training and technological challenges). These results revealed that the design process should be reviewed.

Conclusions and recommendations

The presented analysis refers to a specific project with particular characteristics, such as internal standards and issues related to information security. However, the lessons learned may assist in the development of future projects that have similar characteristics.

The FTA adoption allowed the identification of different basic events. These events were the possible causes for the occurrence of the top events. Thus, the basic events are the result of a combination of different faults that have occurred throughout the design process. Later, it was possible to identify situations that contributed to hampering the design development in an integrated and collaborative way.

Among the basic events, the partial use of the BIM platform, due to the lack of knowledge of its potentialities for designing with high environmental quality, and the adoption of the BIM model only in the Detailed Design stand out. Different tools and software, to analyze the environmental performance requirements, coordinate the design development, make the budget, among others, were not used throughout the design development.

We suggest the following precautions in design incorporating BIM for improvement of environmental quality:

(1) Collaborative definition of the Environmental Quality Profile: BIM can aid the implementation of environmental requirements and the production of the certification documentation. The QAE profile should be defined in a collaboratively manner and with the complete design team. The multidisciplinary analysis of the AQUA HQE benchmark, using BIM, can anticipate incompatibilities and overlaps between the categories (2).

(2) Clear definition of BIM use: The FTA application revealed that the procurement documentation should define clearly and objectively how to develop the design using BIM, aiming at high environmental quality. It is suggested that the procurement documentation should define the procedures for modeling the database and constructing the model by the hired design office.

(3) Management of information: It is necessary to adapt the design process of the company, to effectively enable the collaboration and integration of information, such as the check of the design documents in the actual virtual model. This change will, for example, facilitate the exchange of information through the design management.

(4) Design team involvement: since working in BIM is the construction of a virtual design, where issues related to the different phases of construction, operation and maintenance have a direct influence on design decisions, the design team involved in the life cycle of the project should be involved from the beginning of the design development, to promote a collaborative and integrated design.

(5) Contemporary method: BIM implementation is a process that brings social and technological changes to the design development. Therefore, traditional design procedures should be reviewed, to prevent that the design teams get limited to implement only a technology and not a process. It is believed that seeing BIM as a process has immediate consequences on how to conduct the design process. In addition, that transformation could stimulate the integrated and collaborative design. Therefore, transformation of the design process to a *contemporary method* would provide a better interaction among all design phases and also the control of the design as a whole.

The FTA method, applied in the case study, revealed that, in fact, the implementation of the BIM platform did not reach the original objective in supporting the improvement of the environmental performance of the rehabilitated building. However, during the design phase of the rehabilitation, clash detection procedures were used to overcome the complexity of the facilities design.

If the BIM Platform had been used since the beginning of the process, it would probably have brought more efficiency and transparency to the process. Not only in what refers to meeting the sustainable requirements but also for the preparation of the necessary documentation for certification.

Finally, the application of the FTA method allowed the evaluation of the undesired events as the result of aspects related to the design process management approach adopted in this project. In the next projects, the design management should be revised to enable the use full BIM potential.

The most important lesson learned with FTA analyses is the necessity to overcome the sequential view of the design process with high environmental quality, to incorporate BIM potentialities since the beginning of the process and allow a collaborative work.

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Notes

(1) The HQE® Association aims to promote the improvement of the environmental quality of buildings, from the sustainable development approach, and to consider the management of environmental quality in the development of the design of buildings (SALGADO; CATELET; FERNANDEZ, 2012).

(2) The requirements of the certification can sometimes be incompatible; as for example, hygrothermic comfort, energy conservation, durability and functionality of solutions.

References

BEBER, M.; SCHEER, S.; WILLE, S. A. de C. Uso da tecnologia da informação como auxiliadora da gestão da comunicação em escritórios de arquitetura. In: ENCONTRO DE TECNOLOGIA DE INFORMAÇÃO E COMUNICAÇÃO NA CONSTRUÇÃO CIVIL, 3, 2004, Porto Alegre. **Anais...** Porto Alegre: ANTAC, 2007. v. 1. p. 1-10.

BLOOMBERG, M.; BUNCEY, D.; RESNIK, D. **BIM Guidelines**. New York: Department of Design and Construction, 2012.

CERTIVEA. **Demarche HQE ® Exploitation.** Référentiel Technique des Batimênts Tertiaires em Exploitation. Version 0. Paris: . Certivea, may 2008. Disponível em: <http://www.certivea.fr>. Acesso em 23 ago. 2016.

CLAUSING, D. **Total quality Development:** A Step-by-Step Guide to World-Class Concurrent Engineering. New York: ASME, 1994.

CORRÊA, K. **Sistemas colaborativos para a gestão de projetos.** 2010. Dissertação (Mestrado em Arquitetura) – Faculdade de Arquitetura e Urbanismo, Universidade Federal do Rio de Janeiro. Rio de Janeiro, 2010.

DE PAULA, N.; UECHI, M. E.; MELHADO, S. B. Novas demandas para as empresas de projeto de edifícios. **Ambiente Construído**, Porto Alegre, v. 13, n.3, p. 137-159, jul./set. 2013.

DEUTSCH, R. **BIM and integrated design**. New Jersey: John Willey & Sons, 2011.

EASTMAN *et al*. **BIM handbook:** a guide to building information modeling for owners, managers, designers and contractors. 2a. ed., Nova Jersey: John Willey & Sons, 2011.

FABRICIO, M. **Projeto simultâneo na construção de edifícios**. **2002.** Tese (Doutorado) - Engenharia da Escola Politécnica, Universidade de São Paulo. São Paulo: mimeo, 2002.

FUNDAÇÃO VANZOLINI. **Referencial Técnico de Certificação:** Edifícios do setor de serviços - Processo AQUA. Escritórios – Edifícios escolares. São Paulo, 2012. Disponível em: < http://vanzolini.org.br/aqua/>. Acesso em 15 set. 2014.

GROAT, L.; WANG, D. **Architectural research methods**. New Jersey: John Wiley & Sons, 2013.

GUASTI, J. **Diretrizes de sustentabilidade de edifícios de escritórios**: estudo de caso do Edifício Marechal Adhemar de Queiroz. 2008. Dissertação (Mestrado em Sistema de Gestão) - Universidade Federal Fluminense. Niterói, 2008.

HELMAN, H.; ANDERY, P.R.P. **Análise de falhas:** aplicação dos métodos FMA e FTA. Belo Horizonte: Fundação Christiano Ottoni, Escola de Engenharia da UFMG, 1995.

KAMARA, J.; ANUMBA, C.; CUTTING-DECELLE, A. Introduction to Concurrent Engineering in construction. In: ANUMBA, C.; KAMARA, J; CUTTING-DECELLE (Eds.) C**oncurrent Engineering in construction projects**. New York: Taylor & Francis, 2007.

KHALFAN, M.; RAJA, N. Improving construction process through integration and concurrent design. **Construction Economics and Building**, vol 5, n. 1, p.58-66, 2005.

KI-CHANG H. *et al.* Risk analysis using fault-tree analysis (FTA) and analytic hierarchy process (AHP) applicable to shield TBM tunnels. **Leec, Tunnelling and Underground Space Technology**, V. 49, P. 121–129, June 2015.

KOSKELA, L. **Application of the new production philosophy to construction**. Stanford: Stanford University, 1992.

______ Foundations of concurrent engineering. In: ANUMBA, C.; KAMARA, J; CUTTING-DECELLE, A. (Org). **Concurrent Engineering in construction projects.** New York: Taylor & Francis, 2007. P. 12-29.

LAFRAIA, J. **Manual de Confiabilidade, Mantenabilidade e Disponibilidade**. Rio de Janeiro: Qualitymark, 2001.

MELHADO, S. O plano da qualidade dos empreendimentos e a engenharia simultânea na construção de edifícios. In: ENCONTRO NACIONAL DE ENGENHARIA DE PRODUÇÃO, 1999, Rio de Janeiro. **Anais...** Rio de Janeiro: UFRJ/ ABEPRO, 1999. 1 CD-ROM.

OLIN, J.; JYLHA, T.; JUNNILA, S.. Virtuality: What does it means for FM?. In: CIB W070, W092 & TG72 INTERNATIONAL CONFERENCE ON FACILITIES MANAGEMENT, PROCUREMENT SYSTEMS AND PUBLIC PRIVATE PARTNERSHIP, 1, 2012, Cape Town. **Proceedings ….** Cape Town: University Of Cape Town, 2012. p. 20 - 26. Disponível em: <http://www.cibworld.nl>. Acesso em 23 ago. 2016.

OLIVEIRA, L. F. S. **Técnicas de construção de árvore de falhas**. Apostila. Rio de Janeiro: COPPE/UFRJ, Laboratório de Análise de Segurança, [20--?].

PETROBRAS. **Edise:** Projeto Executivo de Atualização Tecnológica. 200 f. 2013. Plantas diversas. Original em papel sulfite.

PETROBRAS. **Edifício Marechal Adhemar de Queiroz:** uma visita ao edifício-sede da Petrobras. Comunicação Institucional: Rio de Janeiro, 2008.

REED, R. *et al*. International Comparison of Sustainable Rating Tools. **Journal of Sustainable Real State**, v. l. n. 1, 2009. Disponível em: <http://www.jstor.org/stable/24860541>. Acesso em 23 abr. 2014.

SAKURADA, E. **As técnicas de análise dos modos de falhas e seus efeitos e análise da árvore de falhas no desenvolvimento e avaliação de produtos**. 2001. Dissertação (Mestrado) - Engenharia Mecânica, Universidade Federal de Santa Catarina. Florianópolis: mimeo, 2001.

SALGADO, M.; CATELET, A.; FERNANDEZ, P. Produção de edificações sustentáveis: desafios e alternativas. **Revista Ambiente Construído**. Porto Alegre, v. 12, n. 4, p. 57-73, out./dez. 2012.

SANTOS, M.; ZEIN, R. A moderna Curitiba dos anos 1960: jovens arquitetos, concurseiros, planejadores. In: 8° SEMINÁRIO DOCOMOMO BRASIL, **Anais**..., Rio de Janeiro, Brasil, 2009.

SIMÕES FILHO, S. **Análise de Árvore de Falhas Considerando Incertezas na Definição dos Eventos Básicos.** 2006.Tese (Doutorado) - Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia, Universidade Federal do Rio de Janeiro. Rio de Janeiro: mimeo, 2006.

SILVA, F.; SALGADO, M.; SILVA, C. Plataforma BIM, Retrofit e Sustentabilidade ambiental: Estudo de caso na cidade do Rio de Janeiro. In: ENCONTRO BRASILEIRO DE TECNOLOGIA DE INFORMAÇÃO E COMUNICAÇÃO NA CONSTRUÇÃO, 7., 2015, Recife. **Anais**... Porto Alegre: ANTAC, 2015. 1 CD-ROM.

SILVA, F.; SALGADO, M.; CAMPOS, A. The potential of BIM Platform in building modernization aiming to environmental certification. In: WORLD SUSTAINABLE BUILDING 2014: Barcelona Conference. Barcelona. **Proceedings...** Madrid: GBCe, 2014. 1 CD-ROM.

VESELY, W *et al*. **Fault tree handbook.** Washington: U.S. Nuclear Regulatory Commisision, 1981.

WILLIAMS, R. **Utilizing Building Information Modeling for Facilities Management**. 2013. Dissertação (Mestrado) - Bartlett School of Graduate Studies, University of London. Londres: mimeo, 2013.

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