Structural design in a BIM environment: technological advances in information transfer

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1. Introduction

The constant technological evolution and the competitive demands of the world have led to impose a need to improve productivity in the Architecture, Engineering and Construction (AEC) industry. The industry has been adopting emerging technologies that have increased productivity in the sector, particularly in the design of projects. Currently, building design present volume, complexity, and multidisciplinary integration, which by the traditional method based on drawing, becomes difficult to manage. The need to automate and optimize processes contributed to the emergence of the Building Information Modelling (BIM) methodology, a process focused on centralizing all project information in a virtual BIM model. The BIM-based programs available allow the creation of a reliable three-dimensional (3D) representation of the building, including the various specialties that make up a project, and supporting an improvement in the coordination and compatibility of phases. In recent decades, there has been a significant increase in the adoption of BIM methodology, from different areas of the AEC industry, due, in part, to the improvement of programs, but also to the confirmation of its benefits in real cases.

However, in construction enterprises the changing of traditional working methods to the new methodology, requires a high initial cost investment in training and software. Considering that BIM is relatively recent, the programs are not yet fully prepared, and presents some limitations. In this sense, this paper aims to analyze the technological advances that have been achieved, identifying appropriate strategies for performing different tasks associated with the design of structures.

2. Building Information Modeling (BIM)

2.1. Concept

The fundamental concept of BIM methodology, referring to a hierarchical system of building components in the composition of a digital model, was first mentioned by Eastman (1975) through the designation Building Description System (BDS). The author described a system in which it was possible to create elements to which a shape, location, and property list were associated. Later, Building Information Modeling (BIM) was adopted as the most common name for this new way of approaching design representation (Succar, 2009). The building design elaboration, based on BIM software, is provided in the form of a digital parametric model, containing the geometric details necessary for its realistic visualization, but it also incorporates several types of mechanical properties, such as density or modulus of elasticity of the applied materials. The BIM model offers a complete, updated, and accessible database, allowing the sharing of data between partners and phases, encompassing all stages of the life cycle of a building (Azhar, 2011).

Compared to Computer-Aided Design (CAD) software, the use of BIM systems decreases the possibility of errors and omissions in the design, which often lead to delays, additional costs, and even potential lawsuits between the various parts of a design team. One of the most common problems associated with the use of CAD systems is the time and cost required to generate critical evaluation information about a project proposal, including cost estimates, energy consumption analysis or structural details (Sacks *et al.*, 2018). The BIM contribution in the study of alternative proposals, corresponds to support the members of the design team, in an easy performance of the eventual adjustments over the model being created, based on a sustained 3D visualization and consultant of the model data base, along the creation process. The final design, following the required specifications and adjustments according to the endorsed modifications in a collaborative and integrated way, constitutes to obtain a high-quality product (Azhar, 2011). The improved capability, evident in teamwork, coordination, and collaboration, leads to improved performance of professionals and reduced costs associated with the project design, providing benefits to all involved (Shehzad, 2019).

2.2. BIM Implementation

The transition from a traditional process, rooted in technical design, to the BIM approach requires procedural changes and a significant investment in technology and training. In the context of the enterprise, the implementation of BIM requires the restructuring of its internal functional processes, as part of a strategy to adapt traditional working methods to the new paradigm, as well as a change in inter-company communication (Sampaio & Diez, 2020).

The internal reorganization of enterprises and the change in collaboration practices between partners in a project, presents some limitations, mainly due to the lack of assimilation of the capabilities of its applicability and efficiency. In some of the activities, professionals do not recognize the advantages and technological potential of using an integrated BIM platform in the development of their activity (Sacks *et al.*, 2018).

Currently, the resistance to its implementation has been changing, towards a greater acceptance by all professionals in the various areas covered by the industry. Companies have been recognizing that this transition is inevitable and its implementation in work practices should be understood as a mandatory requirement (Wong, 2015). In all areas of the construction industry, owners, designers, builders, and managers have been reporting the benefits of adopting BIM methodology in their specific activity. This has contributed to the rapid and growing acceptance of BIM, leading government entities to establish guides and deadlines for mandatory implementation in public buildings (Sampaio, 2021).

2.3. BIM in Portugal

Portugal still does not present a clear transition plan for the development of measures to stimulate the adoption of BIM methodology. This relative delay affect, in part, the ability to export services of national companies to international markets, already updated to BIM, losing competitiveness

(RTP, 2020). Additionally, the lack of financial support makes the digital transformation unaffordable for small and medium enterprises (SMEs), which have a lower adoption capacity of new technologies (COTEC, 2020).

However, universities, research centers and top enterprises have organized several training and dissemination initiatives for BIM implementation in the industry (BUILT CoLAB, 2021). The main objective is to study how BIM will affect the different jobs, as well as to analyze the need for the creation of more adequate training offer to the new technological demands (COTEC, 2020).

2.4. Interoperability

Despite the relative benefits of implementing BIM in industry, its adoption in enterprises and project offices has been imposing significant organizational challenges related to internal cultural adaptation regarding ways of working, data transfer processes, and communication with partners (Sampaio & Gomes, 2021) These problems have resulted in a consensus on the need for the BIM approach to be underpinned by interoperability between software (Ren *et al.*, 2018). Currently, interoperability between software points to two main approaches (Sampaio, 2017):

- The open and standardized data format, designed as Industry Foundation Classes (IFC), and created by the international organization BuildingSMART;
- The transfer made through the native data format, related to the use of extensions, add-in, and plug-in, made available in the modeling systems, which ensure the reading and manipulation of the models transferred to those specific applications.

Despite the constant effort in research, carried out in academic and business environments, the persistent limitation of interoperability in some of the tasks that require model transfer, in the pursuit of the development of different stages of the project, the technology market still does not provide a completely effective solution, negatively affecting its implementation (Aksenova *et al.*, 2018). This makes interoperability the main practical barrier to successful BIM adoption in the industry (Shirowzhan *et al.*, 2020).

3. Case study

The case study chosen to develop the structural design in BIM environment is a single-family house, located in the archipelago of the Azores, Portugal, on the island of Faial, is a two-bedroom with 258.3 m^2 of gross floor area and 182.2 m^2 of building area. The process of creating the architecture design, admitted several alternative options, providing, in the ambit of this study, an illustration of how the BIM model constitutes an adequate work basis and understanding of coordination between the activities of the architect and the structural engineer. The preliminary drawings were provided by the engineering office, involved in the design, which provided the architectural plans and elevations, as well as a preliminary design of the structure, in a CAD format file.

3.1. Pre-dimensioning proposal

The proposed structural solution consists essentially of a reinforced concrete beam structure, formed by columns, beams, walls and slabs, and a complementary mixed structural system, formed by frames and walls.

The modeling of the foundations, in a first phase of support to the architectural study, was only considered the modeling of the structure for calculation purposes, i.e., the representation of the analytical model.

The model shows, at level 0 and constituting the construction envelope in contact with the ground, the adopted retaining walls, of 0.20m and 0.25m thickness. On floors 1 and 2, the solid slabs are 0.17m thick, supported by a beamed system. The structural walls adopted for floor 2, corresponds to the structural solution found to meet the architectural constraints. However, in seismic terms, these elements are not recommended, because they introduce more mass in the upper floor and, consequently, increase the horizontal forces. The building also has a sloped roof, in reinforced concrete slab, on the main body, and an accessible terrace roof, on the secondary body. Both slabs are 0.15m thick. The structural solution presented was the result of a series of adaptations, made to the initial pre-dimensioning proposal, which occurred because of architectural changes made (Figure 3.1).

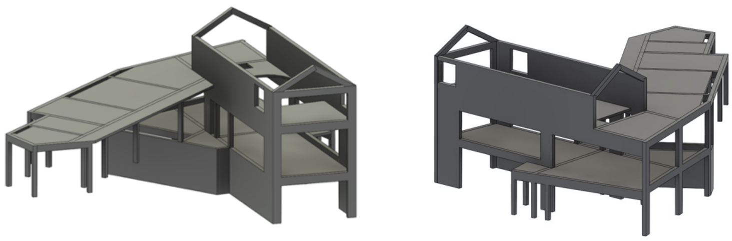

Figure 3.1 - Perspectives of the BIM model of structures created in the Revit system.

3.2. Study of alternative solutions

The project under analysis was submitted to changes made in the architecture, while the structural model was being developed, forcing a series of adaptations of its solution. The most relevant project changes were analyzed, and the BIM model of structures were adjusted according to the imposed modifications.

The architect proposed some changes to the project, which in several situations led to problems that were difficult for the engineering office to solve.

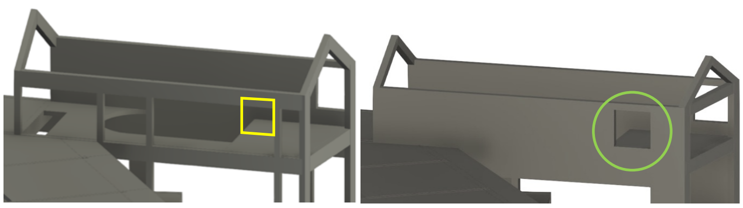

Figure 3.2 - Structural solution before and after the addition of a window.

Like the placement of the window shown in Figure 3.2, making impossible to place a beam with the required dimensions. These difficulties were often not visually understood by the architectural office, which led to a significant increase in the cost of the building structure, which could have been minimized with minor adjustments in the architectural design. The use of the BIM model to assist in the 3D visualization of the project, improved the communication between the offices, even though the architectural office does not use BIM software.

The engineering office benefited a lot from the use of BIM in this project, as it was easy and fast to make changes in the structure and perform the respective structural analysis at any stage of the design. If the architectural design had also been executed in BIM, communication will be more easily established, leading naturally to a better understanding, on both sides, of the constraints, requirements, and possibilities of resolution in a collaborative mode.

4. Structure modeling (Revit)

4.1. Geometric and analytical modeling

The geometric and analytical modeling of the structure was done using Revit (2022) software. Before modeling, it was important to set up the basic parameters of the structure model to be created, such as design units and materials. After that, modeling begins by defining the project alignments and levels, with the help of the imported CAD drawings, which serve as the basis for the placement of the structural elements. Then, the first elements to be modeled are the columns, and sequentially the beams, walls, and slabs. The foundations are modeled after the definition of columns and retaining walls. The modeling is very intuitive supported by the interactive interfaces of the different families of elements to be used. The user selects an element of the desired family and adjusts the dimensions of its cross section or thickness as designed.

The modeling of some elements, such as corner columns, inverted beams, slabs, and inclined roof elements, displayed some complexity and limitations, mainly regarding the compatibility of geometric and analytical models (Figure 4.1).

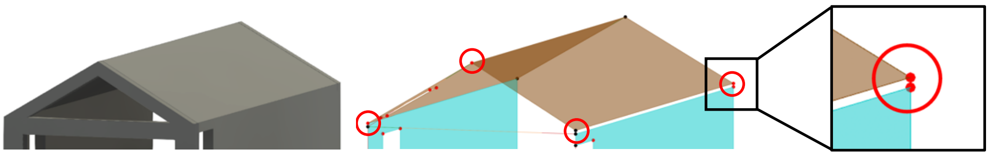

Figure 4.1 - Physical model of the roof and disconnected nodes in the analytical model.

The geometric modeling should always be accompanied by the analytical model, which is automatically generated by the software, to detect errors during its definition. These errors can occur when, for example, the geometric limits of the elements do not coincide with the analytical limits or by failures in the program to detect where the analytical connection of the element should be made. However, there are some tools that facilitate the detection of problems in the analytical model. One of the tools used was a visual filter to detect unconnected analytical nodes. The filter allows, among several options, to highlight disconnected nodes by changing their color to a distinct one, allowing the user to quickly identify them (Figure 4.2). Changes were also made to the representation of the analytical slabs, allowing a better visualization of the different analytical elements (Figure 4.3).

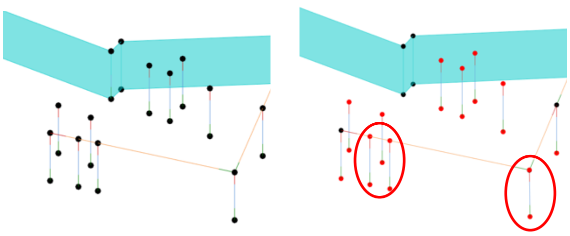

Figure 4.1 - Visualization of the analytical model before and after applying the filter to detect disconnected nodes.

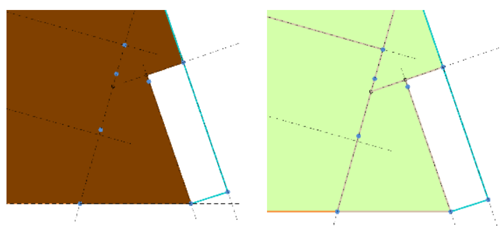

Figure 5.2 - Analytical model of the slabs.

5. Structural analysis and design (Robot)

Once the modelling of the structure has been completed and the consistency of the analytical model has been checked, the model is transferred to the calculation program to perform the structural analysis.

5.1. Revit/Robot data transfer

The transfer of the structural BIM model, between the two BIM-based systems, was carried out by using the Revit/Robot plug-in, through the Direct integration option, allowing the rapid two-way transfer of information when programs are simultaneously open.

No issues were detected when performing the transfer, although some flaws were identified later in the analytical model because of some slab nodes were poorly connected in Revit (Figure 5.3). Once the model was checked for consistency, the loads and loads combinations were defined.

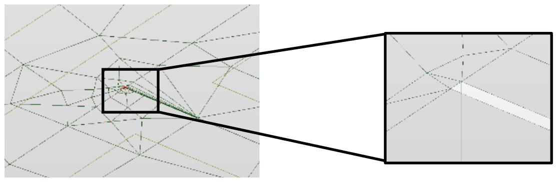

Figure 5.3 - Incoherent zone in the finite element mesh.

5.2. Definition of loads and combinations

The loads considered for the dead loads, were the self-weight, that is automatically defined and applied by the calculation program, plus the remaining loads, such as partition walls and floor coverings. The applied live loads were defined according to the Portuguese norm, NP EN 1991-1-1, classifying the case study in category A with the type of use "Domestic and residential activities".

After the definition of dead and live loads, the seismic action was considered through a modal analysis by response spectrum since the building has an irregular geometry and is in a high seismicity zone. Then, the structural analysis was performed.

5.3. Analysis results

The Robot allows a complete structural analysis of the building structure, providing diagrams of efforts, reactions, deformations, and effort maps, among other options. The information can be presented graphically or in tables.

The visualization of the results can be global (Figure 5.4), or more detailed, allowing the analysis of the elements individually (Figure 5.5). It is also possible to present the results of each load case separately, or to display the envelope forces according to the defined combinations, making it easier to identify critical points. These results can be transferred to Revit and can be consulted.

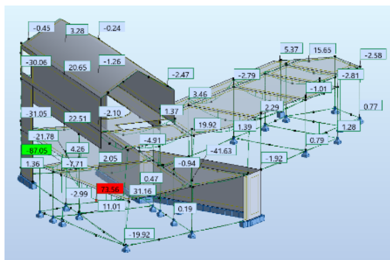

Figure 5.4 - Diagrams of My Moments

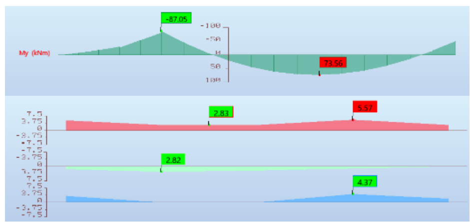

Figure 5.5 - Individual analysis of the beam of alignment A: My moment and required reinforcement

5.4. Reinforcement detailing

Once the structural analysis was done, the reinforcement for each structural component was calculated. Based on the results of efforts and behavior of the structure, the Robot software automatically calculates the necessary reinforcement, satisfying the requirements established in the Eurocode. Subsequently, it generates the correspondent technical drawings of reinforcement detailing. The calculation of the reinforcement of the elements, except for the reinforcement of slabs and walls, is done through the Provided Reinforcement of RC Elements tab.

The reinforcement detailing is very rigorous, although some problems and limitations have been detected:

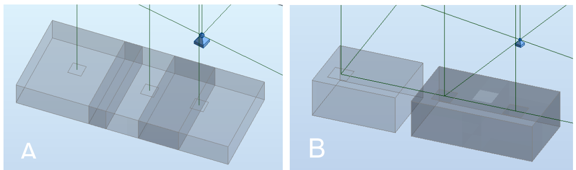

Figure 5.6 - Geometric overlap of the footings (A); Adopted solution (B).

- In foundation design, it is not possible to create combined footings with more than 2 columns (Figure 5.6).
- The eccentricity applied in Revit is not considered by the Robot, and consequently the calculation of the suspension reinforcement is not correct.
- In the detailing of the inclined roof beams, the reinforcement automatically generated by the program did not verify all the Eurocode conditions (Figure 5.7), and manual adjustments had to be made.

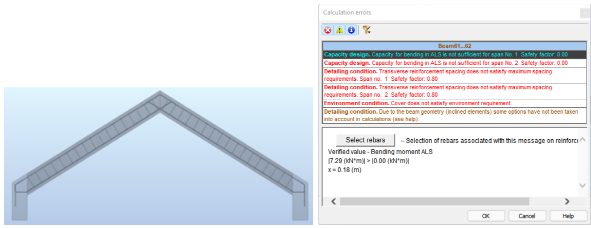

Figure 5.7 - Initial representation and errors presented

- Although slab reinforcement can be dimensioned in Robot, it cannot be transferred to Revit.
- The reinforcement design of structural walls has not yet been implemented in Robot according to Eurocode.

6. Transfer of analysis results

The analysis of the interoperability capability between Revit and Robot (2022 versions), regarding the reverse transfer process, Robot/Revit, where there is usually a greater limitation, is evaluated in this item. On each type of element, the identified inconsistencies were analyzed, and a possible resolution strategy was presented, in order to overcome the difficulties found.

6.1. Foundations

The foundation reinforcement transfer from Robot to Revit is only performed if its geometry is previously defined in Revit. Although the transfer is performed, in some situations the reinforcement has a skewed orientation in relation to the footings (Figure 6.1). This type of errors, although easy to adjust, force the user to spend some time for the correct representation of the reinforcement detailing in the foundation elements.

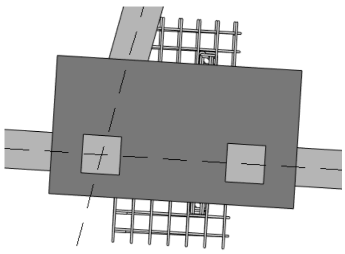

Figure 6.1 - Transferred reinforcement

6.2. Columns and beams

In the Robot/Revit transfer of the reinforcement of the columns and beams, an obstacle kept appearing, which made it impossible to transfer the information quickly. When attempting to update these elements in Revit, the software reported that the Revit model was significantly different from the Robot model. When proceeding with the update, the elements were simply deleted from the model. The lack of interoperability demonstrated between the programs, led to the option of redoing some procedures, to "unite" the two models again. A general update was then performed on the Revit model, where most of the elements had to be adjusted, and then the Revit/Robot transfer was performed for the structural calculation. Afterwards, the update operation of the Revit model was performed again, and, in the transfer process, there were no longer any warnings regarding significantly different models.

After that, the reinforcement transfer improved, however, some elements were not transferred correctly. Analyzing the transfer of the columns, no problems were identified. However, the software showed some difficulties in locating the geometry position of the beams and their orientation. Additionally, after the necessary adjustment of the reinforcement, it was verified in some cases that there were more stirrups than those that were necessary for the length of the spans. This happened because, since the Robot does not consider eccentricities, the software considered larger spans than those defined in Revit.

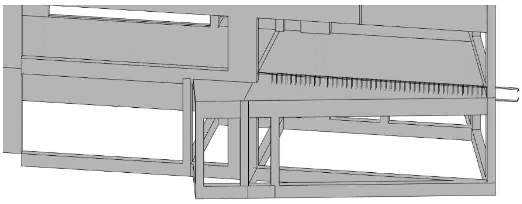
Figure 6.3 - Errors in the transfer of beam reinforcement

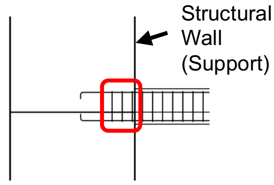

Figure 6.2 - Excessive stirrups

6.3. Transfer of results

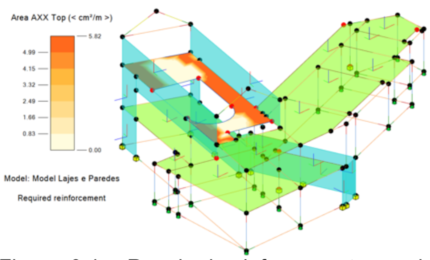

Figure 6.4 - Required reinforcement area in slab floor 2

The direct integration between Revit and Robot, allows the transfer of the structural analysis results to the Revit model. This capability is especially useful when choosing and modeling slab reinforcement in Revit, where the required reinforcement area in each panel is quickly extracted (Figure 6.4). Additionally, it is possible to transfer the resulting stresses, displacements, and strains in columns and beams, concerning each loads combination.

Despite this integration, demonstrating the ability to centralize the results of the structural analysis in Revit, this process still has several errors. There were some difficulties trying to transfer the results. The only solution found was to perform the update of the model, in a selective way by elements, beams and columns and by groups of elements, such as slabs and walls. This procedure led to better transfer results.

6.4. Extraction of technical drawings

Revit provides several options for programming how information is displayed by changing or creating families, allowing for adjustments to aspects related to text, color, thickness, etc. It also allows for more advanced capabilities through programming in Dynamo, a graphical programming platform directly accessible through Revit. However, these features require a high level of user experience.

Analyzing the current state of Revit software, it is noteworthy the ease in creating plans, elevations, and sections, compared to traditional methods, but in the detailing of drawn parts, for the nomenclatures to be according to the desired by the user, it is necessary a high spending of time. However, within a design office, this work should be developed, because the routines and the automation programs to support graphic representation, are reusable and adaptable to each project.

7. Conclusions

The technological advances associated with the BIM methodology have been showing benefits in productivity and construction quality. This study aimed to analyze the benefits of using BIM methodology in the execution of a structural design, as well as the limitations related to interoperability between Revit and Robot software (2022 versions), and the individual limitations of each program.

The benefits are centered essentially on aspects related to the correct functioning, speed, and simplicity in the execution of some processes:

- The ability to transfer information bidirectionally between software, allows changes to the project to be made in only one of the programs, avoiding performing the same task twice.
- The transfer of the BIM model from Revit to Robot is very reliable.
- In Robot, the automatic calculation and reinforcement detailing according to the Eurocodes showed very satisfactory results.
- 3D/BIM modeling, compared to traditional methods, enables any change to the project to be automatically applied to all plans, sections, and views.
- Ease and rapidity in organizing drawn documents.
- Possibility to save all definitions, families of elements and annotations, to be reused in future projects, preserving common elements between projects.

Despite the multiple benefits and technological advances, some limitations were still found:

- The manipulation of the software, taking advantage of the advanced tools available, requires a high level of experience.
- In Revit, the analytical model is very dependent on the geometric model, which limits the modeling of some elements with a higher geometric complexity, by not being able to make the two models compatible.
- The analytical model is very sensitive to changes, often leading to mismatches in structural elements, especially in more complex structures.
- The information transfer in the Robot/Revit direction still presents several flaws.
- Partial information transfer has not been successfully achieved in some cases.
- Several types of loads can be defined in the Robot, not supported by Revit, such as the triangular loads that act on the retaining walls.
- The lack of eccentricity information in the Revit/Robot transfer influences the calculation and detailing of reinforcement in the Robot and this limitation leads to a reduction in productivity because it is necessary to manually adjust the elements to ensure their correct positioning according to the physical model.
- The transfer of rebars to the Revit model is unsatisfactory, and for rebars that are not correctly transferred, it is more productive to model them using extensions such as Naviate Rebar Extension.
- The Robot still does not allow, according to Eurocodes, to calculate the reinforcement of wall elements.
- It is not possible to transfer the reinforcement of slabs from the Robot to Revit.

- The transfer to the modeling software of the reinforcement of isolated footings, is only done if its geometry is previously defined in Revit.
- Transferring the reinforcement of wall foundations from Robot to Revit is not possible.
- The customization of Revit's automatic annotations requires some experience and time, and its editing is not intuitive.

Regarding the limitations of the study, the inexperience of the author in manipulating the software may have limited the use of advanced tools, with all their potential, which would allow a better use of all the capabilities of the programs. Another noteworthy aspect was the release of new versions of the software close to the date of completion of the study, making it impossible to carry out the study using the most recent versions.

7.1. Future developments

This study aimed to contribute to the increase of knowledge about the technological advances of BIM methodology in the field of structural design, with special emphasis on the interoperability between Revit and Robot software. Although several procedures for the execution of a structural design in BIM environment have been analyzed, the technological evolution does not slow down, and programs are continuously being improved to meet the industry requirements. Thus, it is relevant that studies are frequently conducted to analyze the improvements and advances of BIM software. The proposed future developments are therefore:

- Explore future versions of the software covered in this study, comparing their improvements.
- Perform an analysis of the ability to transfer information between programs from different companies using the standard IFC format and plug-ins.
- Carry out an in-depth study on graphic documentation, to assist in the execution of drawings with nomenclatures commonly used in Portugal.
- Carry out a study involving the elaboration of a project that integrates different specialties, to analyze the collaboration and centralization of information.

8. Bibliography

Aksenova, G., Kiviniemi, A., Kocaturk, T. & Lejeune, A. (2018). From Finnish AEC knowledge ecosystem to business ecosystem: lessons learned from the national deployment of BIM. *Construction Management and Economics.* doi:https://doi.org/10.1080/01446193.2018.1481985

Azhar, S. (2011). Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry*. Leadership and management in Engineering*, *11* (3), 241-252. doi:10.1061/(ASCE)LM.1943-5630.0000127

Eastman, C. M. (1975). The use of computers instead of drawings in building design. *AIA Journal*, *63*, 46-50. Available at Link

Mitchell, D. (2012). *5D BIM: Creating Cost Certainty and Better Buildings.* Available at Link

Ren, R., Zhang, J., & Dib, H. N. (2018). BIM Interoperability for Structure Analysis. *ASCE Construction Research Congress,* 470-479. Available at Link

Sacks, R., Eastman, C. M., Lee, G., & Teicholz, P. M. (2018). *BIM Handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers* (3ª ed.). Hoboken, New Jersey: Willey.

Sampaio, A. Z. (2017). BIM as a computer-aided design methodology in civil engineering. *Journal of Software Engineering and Applications*, *10*, 194-210. doi:https://doi.org/10.4236/jsea.2017.102012

Sampaio, A. Z. (2021). Maturity of BIM Implementation in Construction Industry: Governmental Policies. *International Journal of Engineering Trends and Technology, 69, 7,* 92-100. doi:10.14445/22315381/IJETT-V69I7P214

Sampaio, A. Z. & Diez, R. V. L. (2020). BIM short course oriented to professionals of the construction industry, *ABE - Advances in Building Education, Innovación Educativa en Edificación*, ISSN: 2530-7940, Cod. 0089, Septiembre - Diciembre 2020, Vol. 4, No 3, pp. 23-34. doi:10.20868/abe.2020.3.4508

Sampaio, A. Z., & Gomes, A. (2021). *BIM Interoperability Analyses in Structure Design,* CivilEng, 2, pp 174–192. doi:https://doi.org/10.3390/civileng2010010

Shirowzhan, S., Sepasgozar, S. M. E., Edwards, D. J., Li, H., & Wang, C. (2020). BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Automation in Constructions*, *112*. doi:https://doi.org/10.1016/j.autcon.2020.103086

Shehzad, H. M. F., Ibrahim, R. B., Yusof, A. F., & Khaidzir, K. A. M. (2019). Building information modeling: factors affecting the adoption in the AEC industry. *2019 6th International Conference on Research and Innovation in Information Systems (ICRIIS)*, 1-6, doi: 10.1109/ICRIIS48246.2019.9073581

Succar, B. (2008). Building information modelling framework: a research and delivery foundation for industry stakeholders. *Automation in Construction*, *18*, 357-375. doi:https://doi.org/10.1016/j.autcon.2008.10.003

Wong, J. K. W., & Zhou, J. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction, 57,* 156-165. doi:https://doi.org/10.1016/j.autcon.2015.06.003

Web Pages

BUILD CoLAB, O futuro da construção é digital: casas com menos custos, mais eficientes e adaptáveis aos novos usos, 2021 https://www.idealista.pt/news/imobiliario/habitacao/2021/04/20/47001-o-futuro-da-construcao-e-digital-casas-com-menos-custos-mais-eficientes-e-adaptaveis consulted in November 2021.

BuildingSMART, Industry Foundation Classes (IFC) - An Introduction, 2021 https://technical.buildingsmart.org/standards/ifc/, consulted in October 2021.

COTEC, BIM: Building Information Modelling, 2020 https://cotecportugal.pt/pt/projects/bim-building-information-modelling/, consulted in November 2021.

RTP, Portugal atrasado na implementação da metodologia que baixa custo da construção civil, 2020 https://www.rtp.pt/noticias/economia/portugal-atrasado-na-implementacao-de-metodologia-que-baixa-custo-da-construcao-civil_n1207764, consulted in October 2021.