

COST REDUCTION IN CONSTRUCTION THROUGH PROJECT COMPATIBILITY IN A VIRTUAL PROTOTYPE

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ABSTRACT

The design stage is decisive for the Product Development Process, as it is in this stage that the main guidelines of the projects are defined, which directly affect costs, deadlines and production methods. In this sense, virtual prototypes have been used to approve project alternatives, perform engineering analysis, support production planning and present the product to customers. Thus, they allow the reduction of time and resources in decision-making, in addition to predicting problems that may lead to difficulties in execution. In this context, the research sought to optimize pre-existing projects of a popular standard residence through the development of a virtual prototype through the Autodesk Revit tool where it was possible to reconcile the structural, electrical, hydraulic and architectural projects, in addition to adapting such projects with the construction techniques used by the construction company. In this interactive process, the automatic method of detection of interferences (crash-detection) and the manual were applied, through the contribution of the stakeholders of the work. The estimated direct savings obtained per house built was around BRL 905.00, knowing that this development was a housing complex of 90 houses, a reduction of approximately BRL 81 thousand reais was obtained in total.

KEYWORDS

Lean construction, prototype, BIM.

INTRODUCTION

The building construction process is characterized by a high level of variability, which negatively impacts its performance in terms of time and cost (Cruz et al., 2018). Although the construction industry has made changes and improvements in recent years, there is still a need for changes in both production and product development processes and management processes, since it is still far from being equated to the levels of productivity, quality and efficiency of other industries (Navon and Sacks, 2007, Heigermoser et al., 2019).

Project management during the construction period requires contractors to deal with many uncertain and complex tasks that, in highly interrelated networks of activities carried out by multiple stakeholders, can lead to a tendency to deviate from schedule (Sarhan & Fox, 2012).

Such problems of uncertainty in the production process may occur due to lack of better knowledge of working methods (Howell and Ballard, 1999) as well as design errors and incompatibility of what is planned and really necessary (Li et al., 2008).

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Waly and Thabet (2002) emphasize that these errors and mistakes in the construction planning schedule occur frequently, since their compilation depends largely on the limited knowledge and experience of the project team.

Due to this complexity and the large number of factors involved, Li et al. (2009) says that a major limitation for many projects is the lack of effective computer-aided technology for resource allocation and planning. Therefore, this can be an efficient tool to help project planners.

In this sense, even though it is still considered an industry that is not technologically advanced, scholars have studied topics such as waste reduction, process improvement and virtual information flow in recent decades (Landim et al., 2022).

Given the scenario presented, Bayhan et al (2021) argue that companies that seek to improve their production processes should invest primarily in Lean and BIM, with the aim of reducing waste, such as rework, loss of time and costs.

As stated by Dave et al (2011), there are two categories of problems related to construction: a) problems in the execution of construction processes; and b) problems in product representation. While Lean Construction offers an efficient way to solve issues related to construction processes, BIM helps to solve many problems related to projects (products), providing visualization tools and intelligent models of products based on a virtual platform. BIM functionalities are compatible with Lean Principles and vice versa, providing a synergistic effect.

Because of that, the relation between BIM and Lean have been more developed and different authors have studied the relation between BIM and Lean, identifying positive interactions in their combined use (Hamdi & Leite, 2012; Mandujano, Alarcón, Kunz, & Mourgues, 2016; Sacks et al., 2010).

Lean is a production philosophy that focuses on customer needs, production flow and continuous learning (Huntzinger, 2002). In the construction industry, the lean philosophy has been applied for decades, and due to the special features of the construction industry in relation to factory production, the construction industry has developed its own applications of lean production and lean design.

Building information modeling (BIM) has been recognized as a leading innovation in the construction industry worldwide to improve the productivity capability in this segment (Husain, Razali and Eli, 2018) and can potentially be used with human input to store and structure customer requirements and connect this information to building models to visualize requirements, keep them up-to-date, and perform project evaluation tasks (Jansson, Schade and Olofsson, 2013).

Currently, BIM is one of the most important current approaches to address productivity problems in the construction industry, with an increasing adoption rate in the last years (Peralta and Mourgues, 2022). This high interest can be explained by BIM's promise of improving the construction performance and efficiency (Azhar, 2011). BIM enables error detection, omissions, and clashes beforehand, which helps reduce waste and makes construction processes more linear (Eldeep et al., 2022).

Crotty (2012) points out that the use of BIM, in addition to enabling the improvement of the quality of project information, the tool also allows establishing mechanisms and procedures for how information is communicated and shared among members of a team.

MacLeamy (2004) also suggests that BIM implementation effort from the early stages of the project causes cost savings with late changes in the product lifecycle. Nevertheless, if BIM is not properly implemented, organizations may incur in additional costs or reductions in efficiency (Chu, Matthews, & Love, 2018). One of the causes for these potential unwanted outcomes is stakeholders without the required capabilities and awareness for the BIM uses in the construction projects (Gu, Singh, Taylor, London & Brankovic, 2008).

Thus, this research sought to reduce execution costs due to errors that occurred during the construction of popular standard residential buildings from a case study using a virtual prototype modelled through the Autodesk Revit tool for project compatibility.

LITERATURE REVIEW

In general, wastes in construction are associated with overproduction, transport and processing of materials, defective products, unnecessary movement of workers, lack or excess inventory, among others (Antunes Junior, 1995).

In this context, Lean techniques supports not only the continuous improvement of the production system by avoiding waste, but also the optimization of the interaction between humans and machines (Cisterna et al., 2022). Lean Construction is the adaptation of Lean principles derived from the Toyota Production System into the construction sector. (Salem et al., 2006).

Today, the application of Lean techniques to construction (Lean Construction) plays a crucial role on many construction sites as with them processes can be stabilized and continuously improved (Cisterna et al., 2022).

According to Sacks et al. (2020), several physical resources (personnel, equipment and materials) interact in construction workflows, many of which are temporary. In addition, construction projects have required the availability of increasingly detailed status information to find and remove constraints, prepare tasks, staff and perform services. Lean principles provide a solid foundation for dealing with these issues; however, their methods require a considerable flow of information and resources, which are difficult to maintain without the support of information technology.

In addition, the elaboration of the projects also has a great impact on the development of the construction. According to Adesse (2006), projects should be considered as the "backbone" of the production process, since design failures are also responsible for negatively affecting the production process.

According to Muller and Saffaro (2011), among the main design flaws stand out: the lack of compatibility between "the functional parts of the building", the lack of detail of the information and the lack of communication between the designers.

These constant design errors bring to light the need to produce more complex and well-designed projects in order to avoid errors and reduce costs. In this sense, the information technologies implemented in engineering and architecture software, enable designer's three-dimensional virtual models of the product, which was previously taken with two-dimensional representation (Muller and Saffaro, 2011).

In this sense, virtual prototypes are fundamental for error checking and continuous project improvements. For Ulrich and Eppinger (2000), prototype can be considered an approximation of the actual product over one or more dimensions of interest. These models are of the physical or analytical (virtual) type, where analytical models can be considered intangible ones, which use computational software for their modelling. This model enables better and faster ways of modifying design at a low cost (Muller and Saffaro, 2011).

In this sense, the BIM philosophy is able to promote harmonization and integration between the areas of architecture, engineering and construction throughout the production of projects. Thus, this tool has great use in the optimization of multidisciplinary projects, bringing an improvement in the quality of products (Miranda and Salvi, 2019).

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METHODOLOGY

The method used in this research was Design Science Research (DSR), a method in which it consists of analyzing from various perspectives the conception and execution of projects. The methodology DSR is a research model oriented towards solutions to practical problems in technology and engineering. The process includes identifying the problem, defining objectives, developing artifacts, demonstrating effectiveness, and evaluating results. The aim is to produce useful knowledge to improve practices and decisions in a specific field.

According to Peffers et al. (2007), the DSR process consists of six steps:

1. Identification of the problem: this first consists of identifying and justifying the research problem, aiming to develop an artifact that can provide an effective solution. The definition of the problem also helps to motivate the researcher and the public, in addition to allowing the understanding of the reasoning involved;
2. Objectives: this second stage consists of defining objectives for a solution based on the definition of the problem and knowledge of what is possible and feasible. These objectives can be quantitative or qualitative and must be rationally inferred from the problem specification;
3. Design and development: this third stage consist of designing and developing the artifact to solve the problem. It is necessary to determine the desired functionality of the artifact and its architecture, and create the actual artifact based on the theory applicable to the solution;
4. Demonstration: in the fourth step, the use of the artifact to solve the problem in question is defined and demonstrated through experimentation, simulation, case study or proof;
5. Evaluation: The fifth step involves measuring and evaluating how the artifact supports the solution of the problem, comparing the objectives of the solution with the actual observed results of using the artifact in the demonstration.

To ensure a structured and organized approach to the research project, an organization chart was established. This chart served as a visual representation of the hierarchy of tasks and responsibilities, providing clear guidance on the progress of the project. Figure 1 shows the details of the chart, describing the different steps and their respective descriptions. By using this chart as a reference, the research team was able to stay focused and stay on track throughout the project. Additionally, it helped ensure that all team members were aware of their respective roles and responsibilities, promoting efficiency and collaboration.

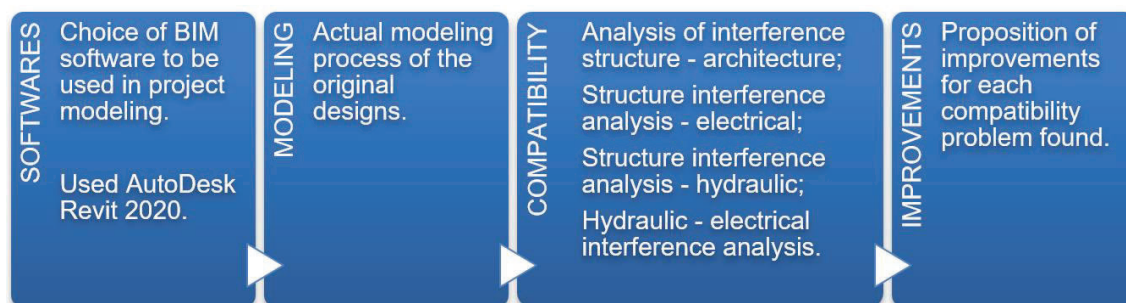


Figure 1: Research organization chart.

Initially, the Autodesk Revit 2020 Educational software was chosen for the modelling of projects, since it had better tools to develop all projects in BIM.

The building in question are houses in the popular standard with 72 m² of built area, replicated in housing estates of multiple units. All the original projects were in the AutoCAD

model, BIM modelling started from these projects, according to the architectural plan below (Figure 2).

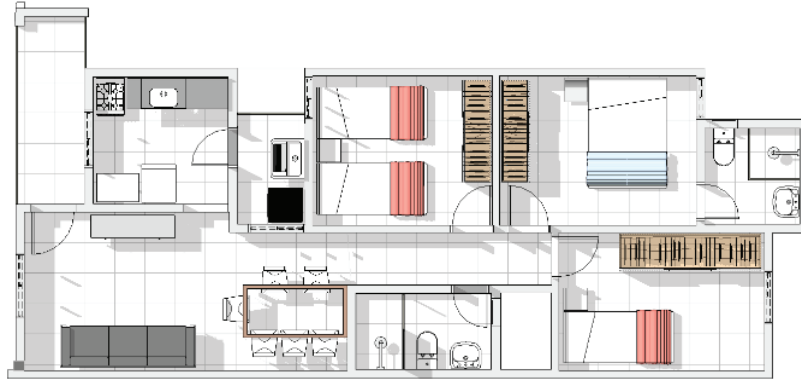


Figure 2: Building layout plan.

After the modelling process of all disciplines, the compatibilizations began. These interactions were done in two ways: manually (based on the authors' experience) and in an automated way (using BIM processes crash-detection). The first structure-architecture analysis aimed to identify differences between the opening spans of doors and windows left in the structural design, when compared to the architect design. This analysis was done manually, verifying point by point of the projects.

The structural-electrical, structural-hydraulic and electrical-hydraulic interactions were made in an automated manner through Revit's own Interference Verification tool. To get to this verification window, we follow the following path:

Collaborate > Coordinate > Interference Verification

Next, the projects that were objectives of identifying interference were selected. In these analyses, we looked for problems of the type contact between structure and electrical or hydraulic elements, or among the elements themselves, which could compromise the execution of the work.

At the end of the interference analysis part, measures of modifications in the projects were proposed in order to optimize the projects as much as possible, reducing costs and facilitating execution.

FINDINGS

From the interactions between structural and architecture, we were able to identify a failure in relation to the dimensions of the doors (Figure 3) and windows (Figure 4).

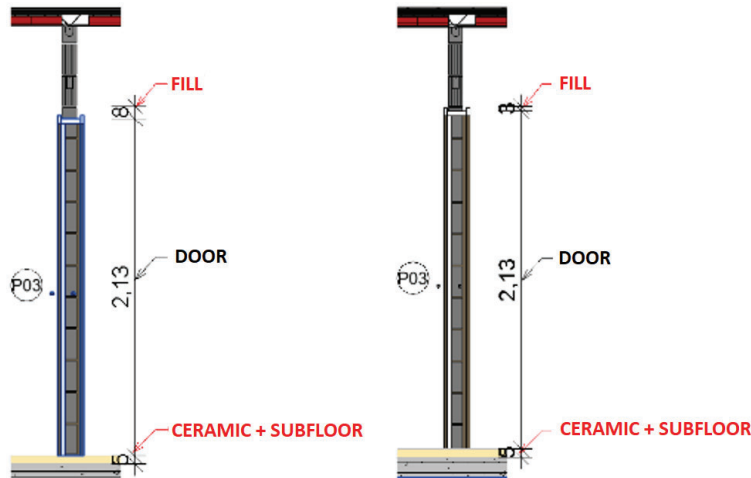


Figure 3: Door before (left) and door after modifications (right).

In the doors, the problem perceived was that: when the floor was executed first, before the structural masonry, the need for a very large filling arose at the top. When this happens, in Brazil, it is common to fill with ceramic bricks, which can generate cracks over time, since this material does not work with the structure. Thus, it was proposed that the floor be executed later than the masonry, thus reducing the upper height of the doors by 5 cm, being now filled only with mortar. This fill was also aligned with the windows.

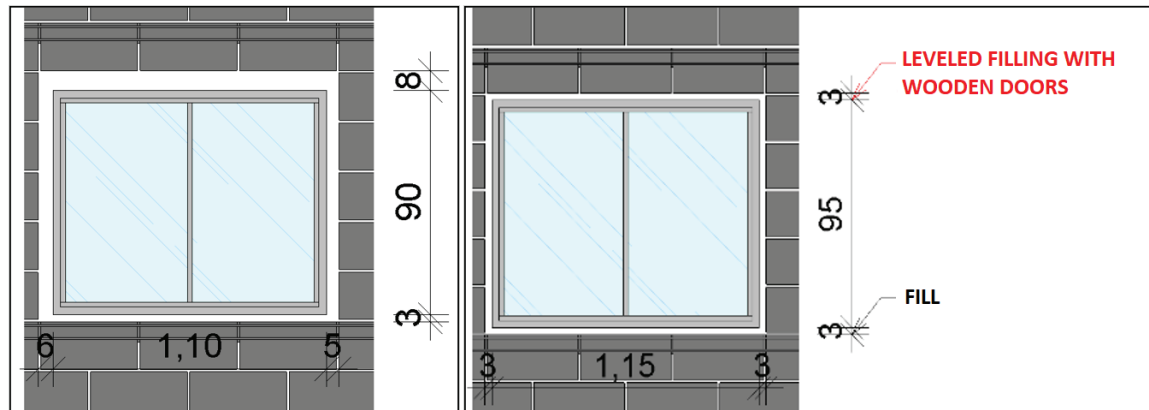


Figure 4: Window before (left) and window after modifications (right).

In this case of the windows, it was identified that they were not aligned with the top of the doors, and for this alignment it would be necessary to increase the frame and leave a mortar fill of 3 cm. Therefore, for the size of the window was increased 5 cm. This problem is related to the modulation of the structure that was made in structural masonry of concrete blocks.

After these modifications, the budget compositions of SINAPI (National System of Survey of Civil Construction Costs and Indexes in Brazil) were applied in order to obtain the final economy of this modification. Each house has 4 windows and 7 doors. The costs obtained after this analysis are shown in Table 1 below.

Table 1: Cost analysis changes in frames

	Windows	Doors
Manpower	BRL 210.00	BRL 370.00
Spared material	BRL 10.00	BRL 10.00
Spent material	- BRL 35.00	- BRL 0.00
TOTAL PER HOUSE	BRL 185.00	BRL 380.00
TOTAL SET 90 HOUSES	BRL 16,650.00	BRL 34,200.00

Another problem identified in this interaction was the lack of alignment between the architecture and the structure. For this, each layer of masonry was modelled, distinguishing the thicknesses of each coating. Thus, it was simpler to align the two projects, and can obtain more trustworthy quantitative (Figure 5).

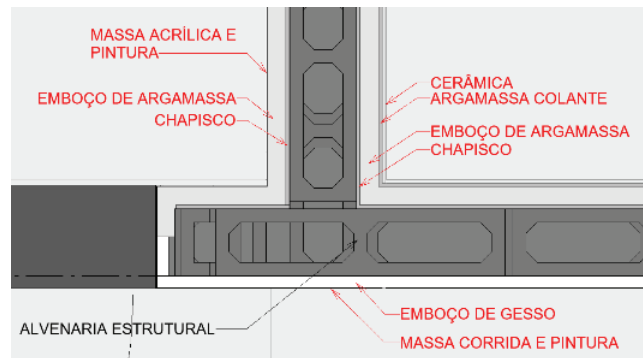


Figure 5: Coating layers of the structure.

Before the electrical-structure interaction, numerous improvements in the project were verified, in agreement with the Brazilian standards in force and the culture of the construction company involved. Figure 6 shows what the project was like before and Figure 7 as the final design resulted after the modifications.

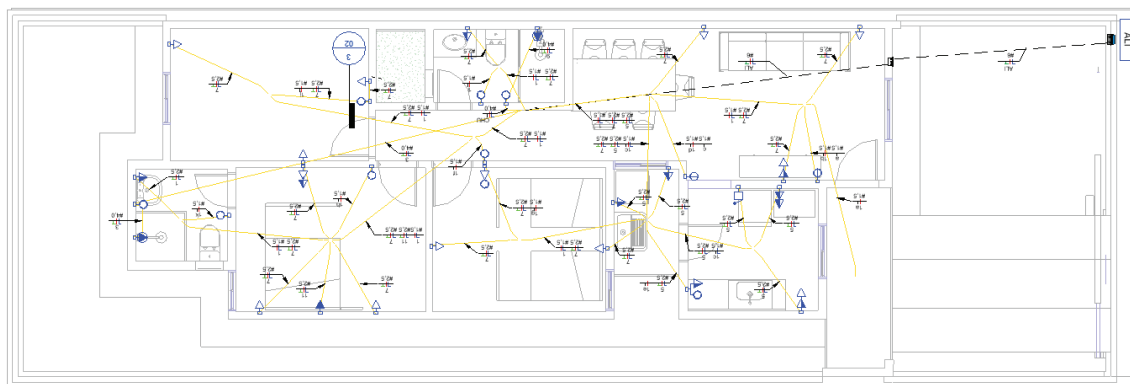


Figure 6: Old electrical design - floor plan. Source: Cipresa, 2018.

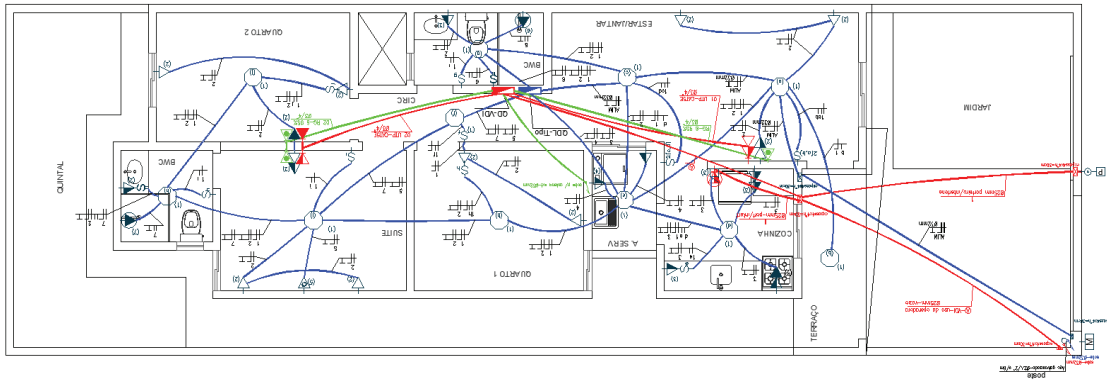


Figure 7: New electrical design - floor plan.

The modifications made in this edition have made the following points:

6. reduce the route through which the cables passed to power the circuits;
7. create a separate main power only for the input circuit;
8. separate the circuit of showers into individual conduits in order to reduce the internal heating of the grouped cables;
9. create a separate VDI (Virtual Desktop Infrastructure) system with internet input at the front of the residence, and television alimentation by coverage.

By processing the structure-electrical interaction, through crash-detection Revit, it was possible to identify 503 interferences of the structure with the elements of the electrical design. By analysing these interferences, it was possible to see that some 4x2 and 4x4 boxes were not located within the empty blocks. Thus, they were moved to the ideal point as shown in the example in Figure 8.

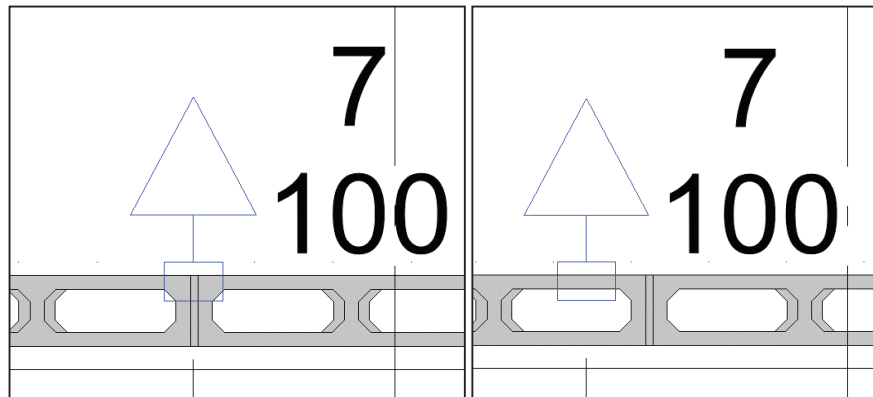


Figure 8: Box 4x2 on the seam of the blocks (left), box repositioned in the empty of the blocks (right).

Other interferences were considered normal, such as conduits passing through the cover slab, since the construction process already uses them in this position.

To verify the costs in this analysis, the fixed amount for labour was used, since the company's culture consisted to pay a single amount per residence to the electrician, and the modifications made would not reduce this service. As for the materials, the base data from SINAPI was also taken for estimated of cost. Based on the modifications made, and comparing the quantity of material before and after, we arrived at the following data (Table 2).

Table 2: Cost analysis changes in electrical design.

	Before	After
Manpower	BRL 900.00	BRL 900.00
Material	BRL 1,800.00	BRL 1,460.00
TOTAL PER HOUSE	BRL 2,700.00	BRL 2,360.00
TOTAL SET 90 HOUSES	BRL 243,000.00	BRL 212,400.00
DIFFERENCE IN VALUES		BRL 30,600.00

Starting for the hydraulic project, when interacted with the structure, it was possible to identify the pipe connection to structural masonry, which in Brazil is not allowed by the current Norms. In this way, all the pipes were moved out of the masonry. Some connections and pipes were reduced at the request of the builder, so these modifications were not counted as savings due to compatibilizations. The process of compatibilization made it possible to better representation the construction of these elements (Figure 9), so that the gain at execution time becomes almost impossible to quantify.

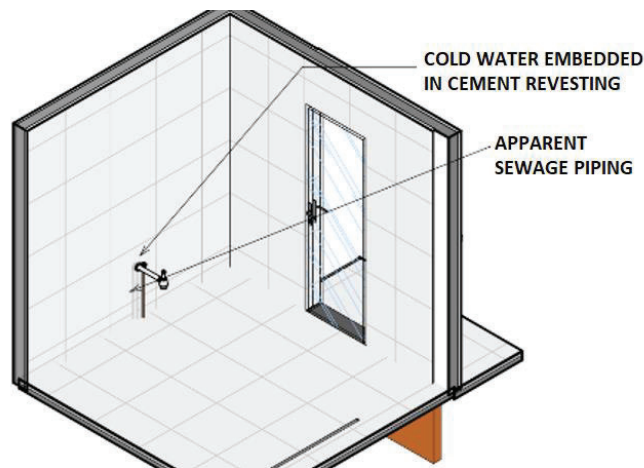


Figure 9: Representation of pipes in the kitchen (example).

The modifications in the hydraulic design were not accounted for, for the reasons mentioned above. Interference analysis was performed between the electrical and hydraulic projects, but no interference was detected. After this step, all representations of all projects were made, now in BIM. These printed and digital projects were made available to the construction team for execution. The 3D visualization of the modelling of this residence can be seen in Figure 10 below.

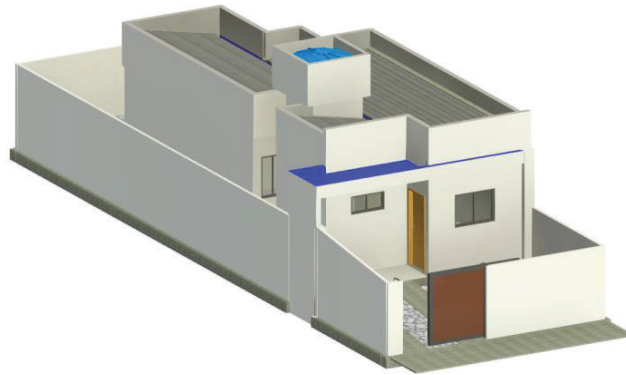


Figure 10: 3D BIM Modelling.

CONCLUSIONS

Modelling in BIM made it possible to explain the construction in a clear and objective way for all the employees involved, bringing with it a rich detailing of information that enabled significant improvements in the old projects of the residences. The joint work of the project team with the construction company's execution team brought greater integration between information, ensuring everyone's participation in the process and reducing future barriers and additional costs at the construction site.

Just relying on automatic compatibility (crash-detection) would not be enough to obtain all the necessary results, since most of the modifications carried out resulted from the construction process. In this way, the active participation of engineers, the master builder and the authors of the paper became essential so that compatibility was carried out properly. Thus, it was possible to ensure that all necessary changes were made and that the final project was completed successfully, without major problems or complications. The integration between professionals and available technologies was essential for the success of the project.

The analysis of the results presented by the BIM modelling process shows the great potential of this methodology to reduce costs in the construction sector. The savings obtained in this specific housing complex of 90 houses represented a final gain of BRL 81,450.00, a significant amount that could be allocated in other areas of the construction. With the implementation of this process, the employees involved were able to obtain greater efficiency and precision in their work, which is essential for the success of any project. It is noteworthy that these savings could be even greater if the project had a larger area or had vertical replication, which reinforces the relevance of this methodology in highly replicable projects.

In addition to the financial benefits, the BIM modelling process also provides significant gains in terms of sustainability and environmental impact. By optimizing the use of resources and reducing waste, the methodology contributes to a more efficient and responsible use of materials, essential for the preservation of the planet. Therefore, the implementation of BIM in construction projects represents not only a financial gain, but also a social and environmental responsibility. This methodology is becoming more and more relevant in the construction sector, and its implementation should be encouraged to promote sustainable development and cost reduction in construction projects.

This type of collaborative approach brings numerous advantages to the construction process, as it allows for the early identification and solution of problems, the elimination of waste and rework, and the maximization of the efficiency of the construction team. In addition, the application of the Lean philosophy in conjunction with BIM technology can result in significant improvements in the quality of the final product, in the reduction of costs and deadlines, and in customer satisfaction.

With this, it is expected that this work can contribute to the dissemination and adoption of more efficient and collaborative practices in civil construction, to the benefit of the entire production chain and, mainly, end users. With the growing demand for more sustainable and efficient construction projects, the Lean philosophy and BIM technology are fundamental tools to achieve these goals, allowing the construction sector to become more competitive and aligned with market trends and demands.

REFERENCES

- A. H. Husain, M. N. Razali, S. Eni, "Stakeholders' expectations on building information modelling (BIM) concept in Malaysia", *Property Management*, <https://doi.org/10.1108/PM-02-2017-0013>. 2018.
- A. L. Muller, F. A. Saffaro, "A prototipagem virtual para o detalhamento de projetos na construção civil". *Ambiente Construído*, v. 11, n. 1, p. 105-121, Jan. 2011. ISSN 1678-8621.
- Cisterna, D., Lauble, S., Haghsheno, S., & Wolber, J. (2022). Synergies Between Lean Construction and Artificial Intelligence: AI Driven Continuous Improvement Process. Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30), 199–210. doi.org/10.24928/2022/0122.
- D. C. C. K. Kowaltowski, E. Atália, D. Muianga, A. Denis, D. D. C. Moreira, S. P. Bernardini, et al., "A critical analysis of research of a mass-housing programme". *Building Research & Information*, 3218, 1–18. <https://doi.org/10.1080/09613218.2018.1458551>. 2018.
- E. Adesse, "A importância do coordenador do projeto na gestão da construção: A visão do empreendedor". (Dissertação) Programa de Pós-Graduação em Arquitetura PROARQ/FAU/UFRJ- Rio de Janeiro, 2006, 10p.
- G. Jansson, J. Schade, T. Olofsson, "Requirements management for the design of energy efficient buildings", *Journal of Information Technology in Construction*, Vol. 18, January, pp. 321-337. 2013.
- J. A. V. Antunes Junior, "A lógica das perdas nos sistemas de produção: uma análise crítica". In: ENCONTRO NACIONAL DA ANPAD, 19, 1995, João Pessoa. Anais... 1995, p. 357-371.
- K. T. Ulrich, S. D. Eppinger, "Product Design and Development". 2nd ed. London: McGraw-Hill, 2000.
- P. Maclearmy, "Collaboration, integrated information, and the project lifecycle in building design and construction and operation". In: Introduced in the Construction Users Roundtable's WP-1202. 2004.
- Peffer, K., Tuunanen, T., Rothenberger, M. A., Chatterjee, S.. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*. 24. 45-77.
- R. Crotty, "The Impact of Building Information Modelling: Transforming Construction". Routledge, 2012.
- R. das D. de Miranda, L. Salvi, "Análise da tecnologia Bim no contexto da indústria da construção civil brasileira". *Revista Científica Multidisciplinar Núcleo do Conhecimento*. Ano 04, Ed. 05, Vol. 07, pp. 79-98 May 2019. ISSN: 2448-0959.

- R. Navon, R. Sacks, “Assessing research issues in Automated Project Performance Control (APPC) ”. *Automation in Construction*, vol. 16, n. 4, pp. 474–484, July 2007. doi:10.1016/j.autcon.2006.08.001.
- Sacks, R., Brilakis, I., Pikas, E., Xie, H.S., Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, 1 (6), art. no. A32. <https://doi.org/10.1017/dce.2020.16>.
- Salem, O., Solomon, J., Genaidy, A., & Minkarah, I. (2006). Lean Construction: From Theory to Implementation. *Journal of Management in Engineering*, 22(4), 168– 175. [https://doi.org/10.1061/\(ASCE\)0742-597X\(2006\)22:4\(168\)](https://doi.org/10.1061/(ASCE)0742-597X(2006)22:4(168)).