

CONSTRUCTABILITY ANALYSIS OF ARCHITECTURE–STRUCTURE INTERFACE BASED ON BIM

João Bosco P. Dantas Filho¹, Bruno Maciel Angelim², Joana Pimentel Guedes³,
Sâmia Silva Silveira⁴, and José de Paula Barros Neto⁵

ABSTRACT

One of the main factors responsible for the reduction of the overall performance and efficiency of buildings is poor project management. Studies have found the integration between design and construction processes has become an important requirement for improving project performance. Considering Lean philosophy has the potential to better integrate design and construction activities.

This paper evaluates the request for information (RFI) associated with the interface between architecture and structure of a BIM model. Methodology was qualitative and research strategy was case study of a virtual construction of a residential building in Fortaleza, Brazil, with 15.925,67 m² of floor area and an estimated cost of \$9, 2 million dollars. 260 RFI were analysed, 110 of which were associated with conflicts between structure, architecture and the MEP systems. That represents 42% of the total RFIs, the highest percentage among other RFI categories, such as plumbing systems, architecture vs. MEP, electrical systems, architecture, and fire protection and gas systems.

This study aims to improve the architecture-structure design interface, and to assist virtual construction crews on what to watch for and how to identify design problems before they are taken to construction site.

KEYWORDS

Constructability, VDC, BIM, RFI, Lean.

¹ MBA, Master's Student, Federal University of Ceará. Architect, Federal Institute of Education, Science and Technology of Ceará (IFCE), Fortaleza, Brazil, +55 85 99168-0846, arquibosco@gmail.com

² C.E., VDC/BIM Coordinator, FortBIM Engenharia S/S, Fortaleza, Brazil, +55 85 98899-8589, bruno@fortbim.com.br

³ Architect, Federal University of Ceará (UFC), Fortaleza, Brazil, +55 85 98871-3620, joanapguedes@gmail.com

⁴ Architect and Urban Planner, Federal University of Ceará (UFC), LEED AP O+M, Fortaleza, Brazil, +55 85 99991-0750, samiasilveira@hotmail.com

⁵ DBA., Full Professor, Department of Structural Engineering and Civil Construction, Federal University of Ceará (UFC), Fortaleza, Brazil, +55 85 99969-1871, barrosneto@gercon.ufc.br

INTRODUCTION

Building Information Modeling (BIM) can assist AEC industry to find potential problems before construction begins (Sacks and Barak 2006). In addition, some benefits of BIM related to design compatibility are maximized through Virtual Design and Construction – VDC.

Requests for information (RFIs) are generated in virtual construction phase. RFI allows the opportunity to identify design problems or improvement that would otherwise be detected only during construction phase, where there is risk of delay and productivity loss. Despite the importance of RFIs, there has been little research to understand how they happen, for what reason they happen, and which strategies can be created to avoid them.

This research is justified by cost implications of a RFI in construction site. Such cost, calculated solely based on administrative and technical review of RFI, was a little over US\$1,000 each (Hughes et al. 2013).

The goal of this study is to describe and analyze RFIs by applying qualitative analysis and propose a proactive approach in identifying and solving design problems. The classification of design errors provides the foundations to consider the appropriateness of strategies to contain and mitigate errors (Lopez et al. 2010). This work is focused on RFIs associated with a BIM model of a structural design with a level of development 400. This work contributes to gap observed in the literature to better determine the strategies needed to significantly reduce design errors in construction and engineering projects (Lopez et al. 2010).

BACKGROUND

This section summarizes literature review that was performed in relevant subject areas including Virtual Design and Construction (VDC), constructability and qualitative analysis.

VIRTUAL DESIGN AND CONSTRUCTION

Virtual Design and Construction – VDC – consists in using multidisciplinary computer models that contain performance targets, construction timelines, and data on organization of the construction and operations teams to promote a better integration among architecture, engineering, construction, operations, and business strategies. (Fischer and Kunz 2004). The main goals of VDC are to use 4D models to create alternatives for projects and anticipate their behavior and performance (Breit et al. 2008). Studies show VDC triggers Lean construction and improves performance of design-construction delivery (Khazode et al. 2006). VDC is a very effective tool to improve construction management, but its utilization requires significant changes in protocols, mindset and conservative behavior of construction industry (Khazode et al. 2006; Li et al. 2009).

This work understands Building Information Modeling (BIM) as a set of interacting policies, processes and technologies generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle"(Penttilä 2006; Succar 2009).

CONSTRUCTABILITY

Constructability is a concept that emerged in late 1970's (Alinaitwe et al. 2014; Sulankivi et al. 2014) and has evolved ever since, due to many studies (Alinaitwe et al. 2014; Hussein and Rosli 2010; Pulaski and Horman 2005; Sulankivi et al. 2014). It can be defined as the use of construction knowledge, project planning experience, engineering, and supplies for design optimization (Othman 2011). This paper proposes a constructability analysis framework that aims to reduce construction problems caused by poor project planning and to make design companies more competitive (Jiang et al. 2013). When associated with design process, constructability increases quality and productivity while reducing time, waste and costs, and promoting better building performance since it brings contractors to design onset (Motsa et al. 2008).

A constructability information classification scheme is proposed in this study and can be used to capture, store and retrieve knowledge of constructability (Hanlon and Sanvido 1995). Six different constructability concerns are proposed and from the moment constructability issues are categorized, a new type of constructability thinking about design process interface is presented (Jiang et al. 2013). Such categories and constructability concerns have been adapted to analyse RFIs of residential projects and a new list of categories is proposed: *Design Correction*; *Divergence of information*; *Design change*; *Design failure*; *Validation information*; *Design verification* (Dantas Filho et al. 2015).

METHOD

This study was classified as exploratory and descriptive. The unit of analysis of this work is Request for Information. Methodology is of qualitative type. Initially, it started with the question: "How requests for information can contribute to improving architecture – structure design Interface?" Then we carried out a literature review for the subject and for the method.

Research strategy adopted was case study (Yin 2001). The case choice was through "selection information-driven" to maximize usefulness of information according to research objectives (Takahashi 2013). The case chosen was supposed to contain the use of VDC in coordinating designs with documentation of requests for information. Thus, a case was selected to obtain information allowing logical deductions. As an example, "If this does (not) apply to this case, so it can (not) be applied to other cases."

Data collection was based on multiple evidence sources: deep analysis of documents and interviews. Three *coordination models* based on Autodesk Navisworks software were analysed. For the purpose of this study, a *coordination model* is the model that contains virtual construction process of all project disciplines and was modelled in Autodesk Revit software. The *coordination model* documented RFIs identified by design coordinator consultant. Semi-structured interviews with the coordinator of virtual construction were held. The following operational procedures were undertaken to legitimize and assure the reliability of data collected: review of interview report by interviewee and development and use of case study database (Yin 2001).

Data analysis was based on recognition of patterns, development of explanations, and use of logic models. Empirical pattern obtained from the case study was compared to another from a prognostic basis, obtained through literature review. This study performs the analysis of general RFIs categories previously proposed by literature (Dantas Filho et al. 2015; Hanlon and Sanvido 1995; Jiang et al. 2013), but is not limited to them. The study identifies new categories that emerge from the typology of analyzed data. The methods used for classification of data were the principles and practices of coding (Gray 2012).

The "requests for information" contained in BIM models are short communication messages written by the virtual constructor to client and project teams. It is always associated with an image of virtual construction and summarizes the issue. The categories proposed in the table of results in the end of this paper – that explored pattern recognition – are the synthesis of this short communication. Therefore, they are not limited to literature review and new categories may emerge from data analyzed.

RESULTS

BUILDING DESCRIPTION

The analyzed building is a 15.925,67 m² residential tower with an estimated cost of \$9.2 million dollars. After conclusion of architecture, structure, and systems design, the developer-construction company – the client – decided to undertake an extra step called virtual pre-construction. A BIM model was then created, with a level of development 400, as a tool to evaluate project's constructability. This analysis intended to foresee any challenges that construction systems might present, assuring that systems would be executed efficiently, kept within the budget, and on schedule. In order to meet client's demand and fully achieve benefits of BIM, the building company provided the virtual construction team their construction method. The construction method contains information about project's execution that are not explicit in design set, but that were taken under consideration by virtual pre-construction team.

CASE STUDY'S VIRTUAL PRE-CONSTRUCTION

Through the analysis of 260 RFI in three BIM models, a total of 110 requests for information associated with clashes between Structural, Architectural, and systems design were identified. Usually, this type of RFIs is only identified during construction. Undertaking the virtual construction before building process starts prevents the construction manager from wasting time with issues that can be solved outside of construction site and really focus on construction planning and execution. Figure 1 illustrates how RFIs, the object of qualitative analysis in this paper, are distributed. The graphic in Figure 1 shows the value of the process and its possibilities since all RFIs identified can be addressed. This figure makes it clear how much value BIM brings to the table. BIM helps transform design and construction processes, in what enhances project quality, eliminates conflicts, and reduces rework, benefits likewise demonstrated by previous work. (Chen and Luo 2014).

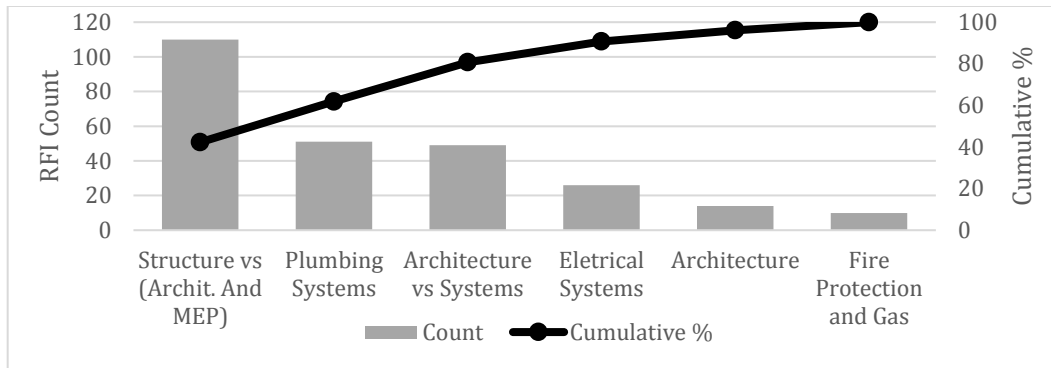


Figure 1: Design distribution of the RFI identified

Interview analysis showed that virtual construction process of design was developed in three steps. In *step 1*, 3D models of architecture and structure were created, establishing an RFI report focusing on the interface between these two design projects. In *step 2*, models of systems utilities were created. The team then performed a constructability analysis of design using a *coordination model* that contained 3D models of all projects. In this stage, a report containing all identified RFIs was prepared. The designers responsible for each discipline then performed the analysis and review of their projects and issued new versions. *Step 3* then started, and the virtual construction team analyzed new versions of projects, observing new solutions given for the issues raised. A final report was issued to the builder-developer consisting of unsolved RFIs and new issues that arose as a result of modifications made by the design team.

GENERAL RFI CLASSIFICATION

RFIs identified were classified in four categories: *Correction*, *Omission*, *Verification*, and *Divergence* (Dantas Filho et al. 2015). Figure 2 illustrates RFI reduction in each general category. Three 3D models created during *steps 1, 2, and 3* of VDC process are indicated below. Left vertical axis shows the total RFI identified by *step*. RFIs generated by analysis were categorized and their count is shown in right vertical axis of the graphic.

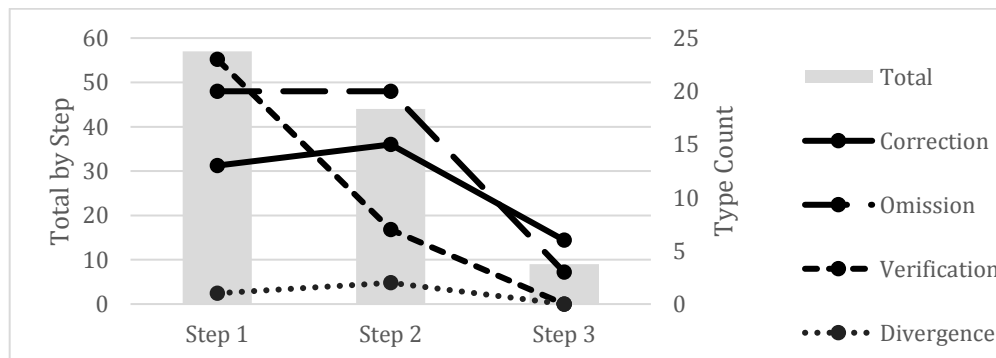


Figure 2: Reduction movement of RFI general types sorted by Step VDC

Below, a description of the RFI categories discussed in this paper followed by examples taken from the case study at hand.

Correction is a problem associated with technical feasibility of solution presented in design, and it usually occurs due to incompatible design versions. For example, the structure was not aligned with masonry walls as defined by architectural design. If this issue does not get solved before construction, consequences can cause reduced width in corridors and fire stairways, which will result in unconformities with firefighting project. Other examples include misplaced pillars in structure vs. architecture design project, insufficient floor-ceiling height, and general misalignment between structural and architectural projects.

Omission is absence of specific design elements required for some areas. For example, in the case study at matter in this paper, there is a vertical displacement platform for people with disabilities not placed at the same level as floor slab. To solve this problem, a ramp would need to be created, which generates a new demand for space not addressed by architecture. Other examples include an unplanned void between floors was identified and will need an embankment on ground, and a recess below lifting platform that was not designed and now will be required

Verification are cases where design is not necessarily wrong, but it offers opportunity for improvement. In this case study, the bottom of internal joints is on same level as the bottom of structural joints on the porch perimeter, which means that they will necessarily intercept ceiling panels. This certainly was not the intention of the architectural project, which planned a continuous ceiling with no interruptions. Checking the possibility of reducing internal beams height would have solved for this problem

Divergence indicates that two or more different drawings have inconsistent information. In this case study, the architectural design proposed a pool with curved edges, whereas the structural design proposed edge to be partially straight on the same section. This happened because the structure designer took into consideration the floor-ceiling height of the underground floor, which houses a parking lot and other functions that require a minimum height. Better communication between two design teams could have avoided this type of situation, which needs to be discussed by both sides rather than solved by unilateral decisions. This put under risk the owner project requirements and the architectural value of the project. Other example of *Divergence*: structure beams of facade diverges from walls from the architectural design.

SPECIFIC RFI CLASSIFICATION

Besides general analysis discussed in previous section, this paper proposes a specific classification of the requests for information associated with structural projects. Such classification is the result of the coding process and is in accordance with a system that comes from data itself. These specific types of RFI are shown in Figure 3 and look deeper into the general RFI categories types previously explained. It is observed RFI on *Conflicts* were the major occurrence, followed by those on *Poor alignment* and *Structure Absence*. These three types together account for 89% of the total.

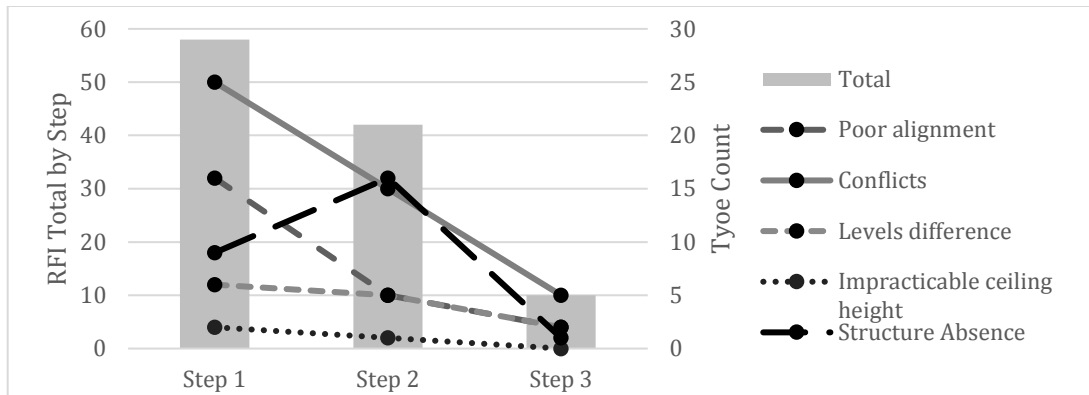


Figure 3: Reduction movement of RFI specific types sorted by Step of VDC

Examples of *Poor alignment* happen between structure and walls and between pillars and joints. Some consequences of *Poor alignment*: area reduction, aesthetic interference, extra spending on fillings. All that can jeopardize the architectural concept, which can lead to non-compliance with the owner's requirements.

Example of *Conflicts*: pillars and beams occupying a considerable area of parking spots, and pillars or beams that intercept windows and doors. Based on examples given, *Conflicts* generate consequences such as: decrease in the number of parking spots, difficulty to perform car maneuvers, reduction of windows and doors openings area, or in the worst case scenarios, it makes fenestration useless.

In this case study, *Levels difference* are problems caused by uneven levels between street and property, street and garden, and between floor and elevators. *Levels difference* affects the property access and generates extra expenses with filling.

Impracticable ceiling height means that ceiling is compromised by height of beams or slabs. It affects, for instance, fire escape routes. In this case study, the VDC team identified a floor-ceiling height of approximately 1.6 meters in fire scape route due to low beams.

Structure Absence is when the building element cannot be implemented due to a lack of a load bearing structure. It is a severe issue because it usually affects the building safety directly and it generates considerable delays in construction schedule since construction site team has to await development of the missing projects or elements.

KEYS TO A SUCCESSFUL RFI REDUCTION

Identifying conflicts is a reactive approach, whereas avoiding conflicts is a proactive approach. That said, ways to improve design process are necessary to reduce future conflicts to occur (Tommelein and Gholami 2012). Table 1 offers a few recommendations as a guideline to identify and avoid RFIs associated with clashes between Architectural and Structural designs.

Table 1: How to reduce RFI – ways to identify and avoid

	RFI Types	Action
1	Correction	Check alignment between structure and architecture; check floor-ceiling height
2	Omission	Check whether there is structural design for all project components; in projects with variable floor plan, check for variations in the formwork plan; check for floor recess for lifting platforms
3	Verification	In the porch area, design the bordering beam with greater height than the inner beams to better accommodate the ceiling panels
4	Divergence	Check heights consistency between Structural and Architectural design projects
5	Poor Alignment	Agree on the same starting point for the building construction; observe walls thickness vs. thickness of the beams that hold them up; architecture team should clean up the drawings from superfluous information that can lead to misinterpretations before hand over those drawings to other design teams
6	Conflicts	Agree on the same starting point for the building construction; architecture must make its requirements clear before the pillars are set on place
7	Level difference	Designers of all disciplines should agree to use the same level of reference; special attention should be paid when inverted and semi-inverted beams are used; observe proper thickness of the layer of soil for gardens
8	Impracticable ceiling height	Architecture design team should provide maximum limits for beams height> if not possible, they should check the drawings back after Structural design is ready before the final project goes to the construction site. That would greatly avoid conflicts in the floor-ceiling height.
9	Structure absence	The structural design of all building elements should be developed before construction, be it real or virtual construction

These actions and strategies presented in Table 1 is intended to be a guideline for other virtual construction teams, a reference on “what to look for?” in a BIM model as far as clashes not automatically detected by software. It is also useful for design team – especially the ones working with projects based on BIM – in what it helps them to avoid frequent design errors. Table 1 could form the basis of a formalized design review procedure.

For instance: in projects executed with maturity level pre-BIM (Succar 2009), the MEP designers do not have control over level of tilted pipes. Only designers undertaking processes with maturity level BIM-2 would have the ability to actually visualize pattern of tilted pipes and identify whenever they overpass a given design guideline. At that moment, designer in charge would have chance to correct de project, modifying pattern and avoiding RFI.

CONCLUSION

Although any design has its own specific characteristics, it is observed the results from this study can serve as a reference for proactive approach in what concerns to identifying conflicts, as proposed in previous studies (Tommelein and Gholami 2012). That said, it is suggested the checklist of Table 1 can be used directly by design teams as a guideline for identifying conflicts and inconsistencies. There is no single strategy, but a multitude of strategies that need to be adopted in congruence to reduce design errors (Lopez et al. 2010).

Virtual construction process has ability to demonstrate the potential for minimizing number and magnitude of changes, disputes, budget increases, and delays during construction (Alinaitwe et al. 2014). Based on this, it is believed that the RFIs generated in the case study and discussed in this paper can contribute to enhance design processes, production, and construction management of projects throughout. In order for that to happen, RFI strategy should be considered during integrated design process in which participants are committed to eliminate potential RFIs making the process more lean.

The use of RFIs as a tool to enhance project management not only can minimize how often design errors happen, but also make the design more time-and-cost efficient, by avoiding rework (Lee et al. 2015).

REFERENCES

- Alinaitwe, H., Nyamutale, W., and Tindiwensi, D. (2014). “Design Phase Constructability Improvement Strategies for Highway Projects in Uganda.” *Journal of Construction in Developing Countries*, 19(1), 127–140.
- Breit, M., Vogel, M., Häubi, F., Märki, F., Soldati, M., Etesi, L. I., Hochmuth, N., and Walther, A. (2008). “CIB W78 2008 International Conference on Information Technology in Construction Santiago, Chile.” (Lessing 2006).
- Chen, L., and Luo, H. (2014). “Automation in Construction A BIM-based construction quality management model and its applications.” *Automation in Construction*, Elsevier B.V., 46, 64–73.
- Dantas Filho, J. B. P., Angelim, B. M., Guedes, J. P., Farias de Castro, M. A., and Barros Neto, J. de P. (2015). “Virtual Design and Construction of Plumbing Systems.” *International Conference on engineering - Engineering for Society*, COVILHÃ.
- Fischer, M., and Kunz, J. (2004). “The scope and role of information technology in construction.” *Proceedings-Japan Society of Civil Engineers*, (February).
- Gray, D. E. (2012). *Pesquisa no mundo real*. Penso, Porto Alegre.
- Hanlon, E. J., and Sanvido, V. E. (1995). “Constructability information classification scheme.” *Journal of construction engineering and management*, American Society of Civil Engineers, 121(4), 337–345.
- Hughes, N., Wells, M., Nutter, C., and Zack, J. (2013). *Impact & control of RFIs on construction projects. Navigant Construction Forum™*.
- Hussein, M. S., and Rosli, M. (2010). “Buildability attributes at design phase in malaysian building construction.” ... *Construction*, 2(1), 24–43.
- Jiang, L., Solnosky, R., and Leicht, R. M. (2013). “Virtual Prototyping for

- Constructability Review (Submitted for Review).” (Cii), 5–6.
- Khanzode, A., Fischer, M., Reed, D., and Ballard, G. (2006). “A Guide to applying the principles of virtual design & construction (VDC) to the lean project delivery process.” *CIFE, Stanford University, ...*, (December), 1–47.
- Lee, H. W., Oh, H., Kim, Y., and Choi, K. (2015). “Quantitative analysis of warnings in building information modeling (BIM).” *Automation in Construction*, Elsevier B.V., 51, 23–31.
- Li, H., Lu, W., and Huang, T. (2009). “Rethinking project management and exploring virtual design and construction as a potential solution.” *Construction Management and Economics*, 27(4), 363–371.
- Lopez, R., Love, P. E. D., Edwards, D. J., and Davis, P. R. (2010). “Design error classification, causation, and prevention in construction engineering.” *Journal of performance of constructed facilities*, American Society of Civil Engineers, 24(4), 399–408.
- Motsa, N., Oladapo, A. A., and Othman, A. A. E. (2008). “the Benefits of Using Constructability During the Design Process .” (1996), 158–167.
- Othman, A. A. E. (2011). “Improving Building Performance through Integrating Constructability in the Design Process.” *Organization, Technology and Management in Construction: An International Journal*, 3(2), 333–347.
- Penttilä, H. (2006). “Describing the changes in architectural information technology to understand design complexity and free-form architectural expression.” *ITcon*.
- Pulaski, M. H., and Horman, M. J. (2005). “Organizing Constructability Knowledge for Design.” *Journal of Construction Engineering and Management*, 131(August), 911–919.
- Sacks, R., and Barak, R. (2006). “Quantitative assessment of the impact of 3D modelling of building structures on engineering productivity.” 1186–1195.
- Succar, B. (2009). “Building information modelling framework: A research and delivery foundation for industry stakeholders.” *Automation in Construction*, Elsevier B.V., 18(3), 357–375.
- Sulankivi, K., Tauriainen, M., and Kiviniemi, M. (2014). “Safety Aspect in Constructability Analysis With Bim.” *CIB W099 International Conference Achieving Sustainable Construction Health and Safety*, Lund, Sweden.
- Takahashi, A. R. W. (2013). *Pesquisa Qualitativa Em Administração -Fundamentos, Métodos e Usos no Brasil*. ATLAS, São Paulo.
- Tommelein, I. D., and Gholami, S. (2012). “Root Causes of Clashes in Building Information Models.” *Proceedings for the 20th Annual Conference of the International Group for Lean Construction.*, 1(510).
- Yin, R. K. (2001). *Estudo de caso: planejamento e métodos*. Bookman, Porto Alegre.