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Integrating Off-Site Modular Construction and BIM for Sustainable Multifamily Buildings: A Case Study in Rio de Janeiro

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Abstract

The construction industry faces persistent challenges, including low productivity, high waste generation, and resistance to technological innovation. Off-site modular construction, supported by Building Information Modeling (BIM), emerges as a promising strategy to address these issues and advance sustainability goals. This study aims to evaluate the practical impacts of industrialized off-site construction in the Brazilian context, focusing on cost, execution time, structural weight, and architectural–logistical constraints. The novelty lies in applying the methodology to a high standard, mixed-use multifamily building, an atypical scenario for modular construction in Brazil, and employing a MultiCriteria Decision Analysis (MCDA) to integrate results. A detailed case study is developed comparing conventional and off-site construction approaches using BIM-assisted analyses for weight reduction, cost estimates, and schedule optimization. The results show an 89% reduction in structural weight, a 6% decrease in overall costs, and a 40% reduction in project duration when adopting fully off-site solutions. The integration of results was performed through the Weighted Scoring Method (WSM), a form of MCDA chosen for its transparency and adaptability to case studies. While this study defined weights and scores, the framework allows the future incorporation of stakeholder input. Challenges identified include the need for early design integration, transport limitations, and site-specific constraints. By quantifying benefits and limitations, this study contributes to expanding the understanding of off-site modular adaptability of construction projects beyond low-cost housing, demonstrating its potential for diverse projects and advancing its implementation in emerging markets. Beyond technical and economic outcomes, the study also frames off-site modular construction within the three pillars of sustainability. Environmentally, it reduces structural weight, resource consumption, and on-site waste; economically, it improves cost efficiency and project delivery times; and socially, it offers potential benefits such as safer working conditions, reduced urban disruption, and faster provision of community-oriented buildings. These dimensions highlight its broader contribution to sustainable development in Brazil.

Keywords: off-site modular construction; building information modeling (BIM); sustainable construction; industrialized building systems; multicriteria decision analysis

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1. Introduction

The construction industry, despite its importance in the global economy, faces a productivity bottleneck when compared to other markets [1]. The low productivity of this sector is directly linked to the construction process adopted in the vast majority of projects, which is an outdated model [2]. In Brazil, this scenario is even more worrisome, since buildings are built using a "conventional" construction method employing reinforced concrete structures and masonry walls, using traditional labor-intensive practices that have been slow to embrace industrialized methods [3]. This process is characterized by a high need for manual activities, limited quality control, material waste, and rework, characteristics that directly affect the process of project management in terms of deadlines and costs [4]. On the other hand, Off-Site Modular Construction (OSMC) has gained traction in countries such as the United States, China, and the UK [5]. The adoption of this method in Brazil has been limited and mostly restricted to low-cost housing and temporary structures [6].

Comparative studies between conventional and OSMC consistently highlight significant advantages of modular approaches in terms of time, cost, quality, and environmental performance. For example, research shows that modular construction can reduce project schedules by 20% to 50% due to parallel site work and factory production [7]. Structural weight reductions are another noted advantage, particularly in high-rise modular systems where lighter modules facilitate foundation design and transportation [8]. OSMC has been applied in the construction sector based on several processes such as prefabrication [9], modularization [10], and industrialized construction [11].

The construction sector significantly contributes to global resource consumption, greenhouse gas emissions, and waste generation, prompting a shift towards more sustainable practices [12]. Hence, OSMC has been highlighted in the literature as a strategy to minimize environmental impacts by reducing material waste, energy consumption, and on-site disturbances [13]. OSMC supports circular economy principles by enabling the disassembly, reuse, and recycling of building components [14].

The global implementation of OSMC is suffering several challenges related to transport constraints, design standardization issues, and site-specific challenges. In these terms, construction material factors are facing challenges related to transportation infrastructure and a fragmented supply chain [15]. Besides, the current design standardization and regulatory frameworks are posing barriers to large-scale implementation of modular systems [16]. There are several publications in the literature that emphasize the need for stakeholder collaboration and early design integration to overcome site-specific constraints and demonstrate the feasibility of OSMC in Brazil [17–19]. In Brazil, comparative evidence remains scarce, especially for high-standard, mixed-use buildings, highlighting the need for case studies to validate the performance of modular systems relative to conventional practices in local conditions [20].

Building Information Modeling (BIM) has become a cornerstone technology in advancing industrialized construction methods such as OSMC [21]. BIM supports the streamlined development of prefabricated systems by enabling integrated design, precise visualization, and enhanced collaboration among stakeholders [22]. In the literature, studies show that BIM assists in resolving coordination challenges inherent in modular projects, such as clash detection, logistics planning, and module interface design [23]. Additionally, BIM-based parametric modeling facilitates the exploration of design alternatives, allowing optimization for structural efficiency and manufacturability [24]. In emerging markets like Brazil, the integration of BIM and industrialized practices remains limited, but recent initiatives indicate a growing interest in leveraging these tools to improve productivity and sustainability outcomes [25,26]. This convergence of digital and physical processes positions BIM as a key enabler of modular construction in complex, high-standard projects [27].

Multicriteria Decision Analysis (MCDA) has emerged as a valuable tool in construction project planning and evaluation, particularly when balancing competing objectives such as cost, time, quality, and environmental performance [28]. MCDA methods, including Analytic Hierarchy Process (AHP) [29], the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [30], and PROMETHEE [31], allow stakeholders to systematically evaluate alternatives based on quantitative and qualitative criteria [32]. In the context of OSMC, MCDA facilitates informed decision-making by integrating technical, economic, and logistical parameters [33,34]. For instance, studies have applied MCDA to select optimal construction methods under constraints related to site access, module size, and client requirements [35,36]. Given diverse urban conditions in Brazil and regulatory environments, MCDA offers a robust framework to guide the adoption of OSMC solutions by quantifying trade-offs and supporting transparent prioritization of project goals [37]. In this sense, Castilla [38] provides an example of how MCDA can be structured and applied in the context of architectural and heritage preservation, offering a replicable approach that reinforces the potential of integrating quantitative methods to measure design-related limitations.

Therefore, this study aims to evaluate the practical impacts of industrialized off-site construction in the Brazilian context, focusing on cost, execution time, structural weight, and architectural–logistical constraints. The novelty herein lies in applying the methodology to a high-standard, mixed-use multifamily building, an atypical scenario for modular construction in Brazil, and employing a multicriteria decision analysis to integrate results. The purpose is not only to expose the different systems that promote the industrialization of construction, but also to assess their advantages, disadvantages, and identify the obstacles that hinder their implementation in most cases. This issue could enable the understanding of which adaptations stakeholders in the construction industry must follow to meet the demands of off-site construction, and to approximately measure the impacts on time, cost, and quality that this method would provide for a real project. It is therefore expected that this research could contribute to the evolution of modular construction in Brazil as a solution for construction projects with short deadlines.

2. Materials and Methods

Based on the benefits and limitations presented in the literature review, it is necessary to measure the impact of OSC. The more efficient way to do it is by comparing it to the traditional construction method adopted in Brazil. In the study, OSC will be evaluated in different aspects, as presented in Figure 1. Initially, there will be limitations presented regarding its architectural and logistical flexibility. Then, a case study about a real construction project executed in Rio de Janeiro will be presented, analyzing three principal evaluation criteria: the weight of the structure, the project cost, and the project schedule.

The limitation analysis is crucial to demonstrate why the current construction market is not yet ready to fully adopt the OSC method to optimize its projects. Even though the scholars list many benefits brought by this construction method, there are still different aspects where the sector must adapt and innovate beforehand in order to make the most of its benefits. The evaluation of the limitations, both operational and architectural, is as important as the measurement of the benefits discussed by other authors. Investigating these factors and promoting solutions can contribute to enlarging its adoption in the Brazilian construction market.

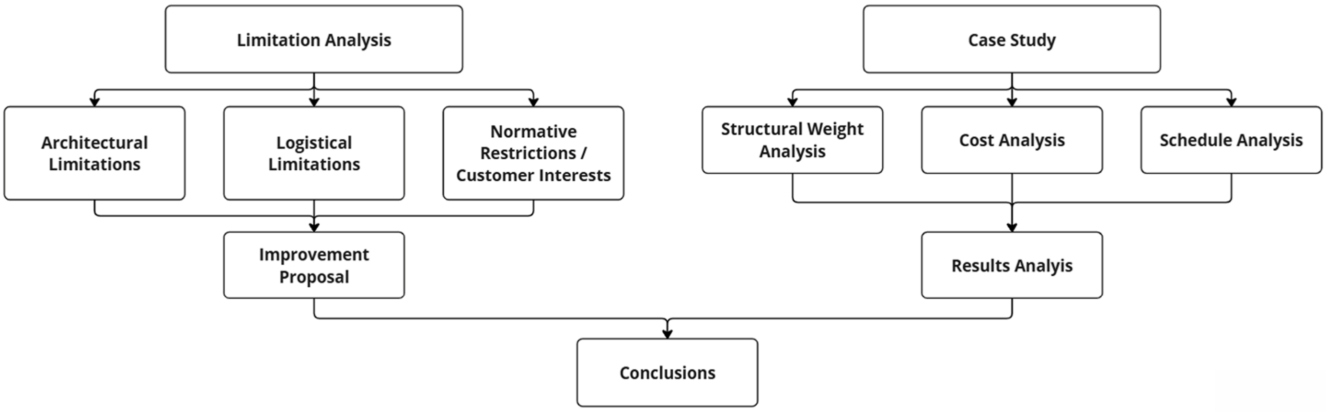


Figure 1. Aspects of OSC evaluation in this study.

In parallel, the case study analysis is one of the most important parts of this article, because even though there is an extensive bibliography covering this topic, construction tends to have a large number of variables that can influence the success of the project. It proves to be strategic for two principal reasons: first, because the project selected for the case study is not the most commonly used in modular construction case studies (it is not a big standardized housing center, hospital, or school), it can demonstrate the flexibility of the system; second, it can provide a practical quantitative analysis of its benefits.

By evaluating the case study on different criteria, it is possible to reform the versatility of this method. The weight reduction, for example, is particularly advantageous in sites where there are geotechnical limitations. The cost reduction contributes to the increase in the attractiveness of the project among investors. Reducing schedule times can add value to customers and project managers, particularly in situations where there are specific demands for urgent delivery of the project. These different evaluation parameters, when analyzed together, provide a more comprehensive view of the OSC system, reinforcing its potential as a viable alternative for the future of the construction sector.

2.1. Logistical and Architectural Limitations

The industrialization of construction implements direct logistical restrictions on its projects. The panels or models needed to respect modular dimensions and the dimensions of the freight vehicles are very different from those needed for the transportation of materials, such as bricks or cement, to conventional construction projects. These differences require special transport vehicles, thus generating higher transport costs. Furthermore, the transportation of onsite materials is also impacted. Due to the large dimensions of these panels and modules, there is a need for lifting, thus depending on the use of cranes, which also increases the transportation costs. These characteristics can impose restrictions on architectural design and demand a careful planning process from the basic conception of the project [39]. Figure 2 shows the lifting process of a modular 2D panel, normally used on façades or enclosures of OSC buildings.

The geometrical standardization of the building, which is a crucial condition to increase productivity and reduce costs and schedule times, tends to reduce the variation of design, as it favors modular solutions over personalized architectural solutions. This benefits the stakeholders of the project by providing greater predictability, even if it means partially sacrificing flexibility [40].

Figure 2. Lifting process of a modular 2D panel used in OSC buildings.

Another important limitation present in industrialized construction is the need for early project integration. This means that all different disciplines of projects (structural, electrical, HVAC, finishings, etc.) must be standardized and integrated before manufacturing the panels. Even small conflicts on these projects can produce reworks, material waste, and delays, compromising the theoretical benefits [41]. Although project standardization is a necessity in any type of construction, it is important to note that this is a common problem experienced in construction projects in Brazil, showing that there is still a great need for advances in the implementation of industrialization.

Finally, there are still logistical limitations that are worth noting. First, adapting to urban transport regulations is a complex process due to the time and noise limitations that large cargo vehicles are subject to. Moreover, construction sites also need adaptations in order to meet lifting needs. Finally, it is important to note that, in cases where the manufacturing is far from the site, an analysis of the transportation costs and emissions is recommended, as those can compromise the sustainability and cost reduction potential of the OSC method [42].

2.2. Structural Weight Analysis

In order to compare the weight of the structure in the two construction methods (traditional and off-site), the following steps were performed:

(a) Collection of reliable data on the specific weight of the materials used in each method.
(b) Quantification of the materials used in both systems.
(c) Direct comparison between the methods based on this data.

It is important to note that the comparison is restricted to only the structural elements directly impacted by the change in the construction system. Elements that are not directly related to the alternation method, such as the finishing, are not included in the analysis. The data collected to provide specific weights were obtained primarily from public and governmental datasets. In the absence of information in these databases, data provided by private companies in the construction sector, such as construction companies or material suppliers, were used, as illustrated in Figure 3. The quantity survey was performed using computational design software. This process was supported by BIM-based quantity take-off, which enabled precise measurement of construction components for both conventional and off-site models, reducing the risk of under- and overestimating material quantities. In this study, Autodesk Revit 2024 was employed for project design and modeling, while Microsoft Project 2021 Professional was used for schedule simulations, enabling consistent alignment between modeling, cost estimation, and scheduling. Quantities were extracted directly from Autodesk Revit 2024 models and linked with SINAPI (National

System of Research on Civil Construction Cost and Indices—a public research institution) cost compositions, enabling the estimation of each input to calculate the structure's total final weight.

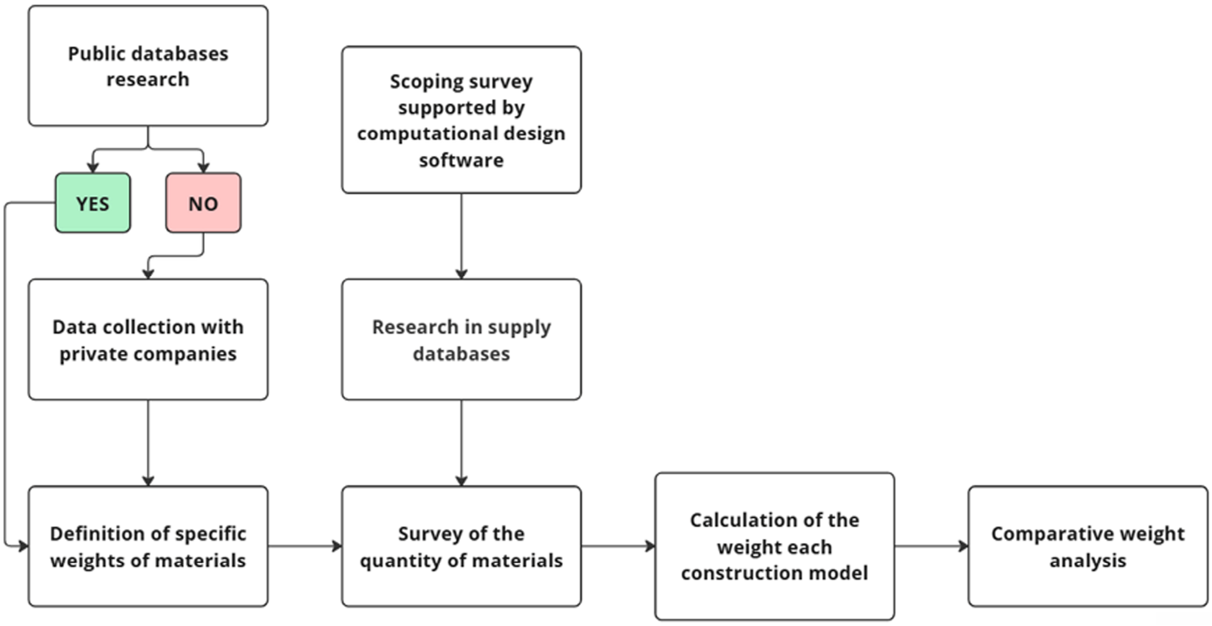


Figure 3. Structural weight analysis.

2.3. Cost Analysis

The cost analysis is conducted with the aim of obtaining a realistic comparison between the two construction methods. In order to measure the costs of the conventional construction method, the budget based on the traditional construction processes was used, applying unitary prices standardized from the Brazilian construction sector. On the other hand, to evaluate the costs of the introduction of the OSC method to the existing project, the authors developed a new budget.

The development of this new budget was based on several data sources. The most important and most used data source was the SINAPI, which provided reliable data on the costs of different steps of construction. However, as it is a recent methodology and not yet consolidated in Brazil, many specific off-site construction services are not covered in the SINAPI database. In these cases, unit price compositions (UPCs) compatible with the necessary services provided by scientific articles or dissertations were used. As a last resort, when such compositions were also not available in the literature, it was necessary to develop new UPCs, using data obtained from the aforementioned sources and from data provided by private companies contacted by the authors. After defining all the UPCs, a quantity survey was produced for every service. With these two pieces of information, it was possible to develop the new budget for the OSC method. BIM models were used to integrate the revised construction system into the cost analysis, allowing the automatic extraction of quantities linked to Unit Price Compositions (UPCs) and ensuring consistency between the design modifications and the budget estimates. The summary of the methodology used to establish the comparison can be seen in Figure 4.

It is important to note that, as described in the last chapter, this analysis is restricted to the topics where there are changes caused by the construction method change. Therefore, both the costs of replaced services and newly incorporated services were considered. Examples of items eliminated in the transition to the OSC include the elimination of deep foundations. On the other hand, the added services include more complex logistical aspects, which are characteristic of the industrialized construction.

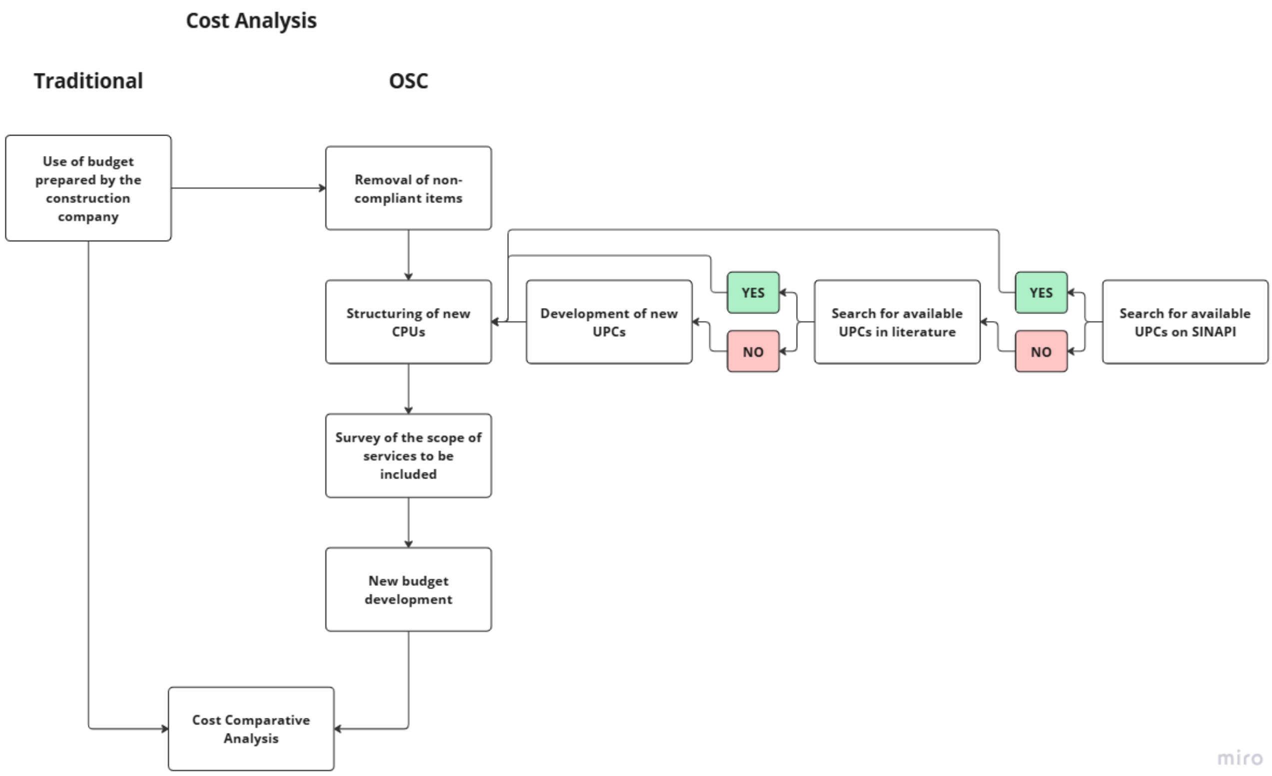


Figure 4. Cost analysis.

2.4. Schedule Analysis

The schedule analysis was conducted by an empirical approach aiming to compare the work schedules under two different construction approaches. To analyze the traditional method, the study presents a schedule that reproduces common timeframes needed to execute the services described based on the Brazilian construction sector standards. To estimate the time needed for the OSC method, two distinct application models were analyzed. The first one, Model 1, considers a lower level of industrialization, where the prefabrication is restricted to the metal structure, leaving some part of the manufacturing of the panel to be performed on-site. Model 2, on the other hand, represents a fully industrialized approach of the OSC method where all the manufacturing of the panels is done off-site, leaving only the assembly of the module to be done on-site. The system used to compare the schedules between the two models is illustrated in Figure 5.

Even though modular construction represents only a minor percentage of the projects in Brazil, Model 1 represents the level of industrialization more common in Brazilian projects. Model 2, on the other hand, represents the most state-of-the-art projects using the OSC method, which is more common in Asia, the USA, and Northern Europe.

Since there are no consolidated databases defining standardized execution times for each model, a survey of companies specialized in modular construction was necessary to obtain the productivity estimates to develop the schedules. It was possible to obtain data to estimate the productivity in Model 1, but for Model 2, as the application is not yet widespread in Brazil, the productivity was estimated based on the Model 1 productivity plus a margin of improvement.

During the schedule analysis, not only were the total times of the activities compared, but there was also an adaptation of the predecessors and successors activities, which can change based on the Model used. This step is critical as the schedule reduction highly depends on the simultaneity of activities to be performed. The scheduling scenarios for Models 1 and 2 were derived from Microsoft Project 2021 Professional, which allowed the visualization of construction sequences and the identification of parallel activities that contributed to the observed time savings.

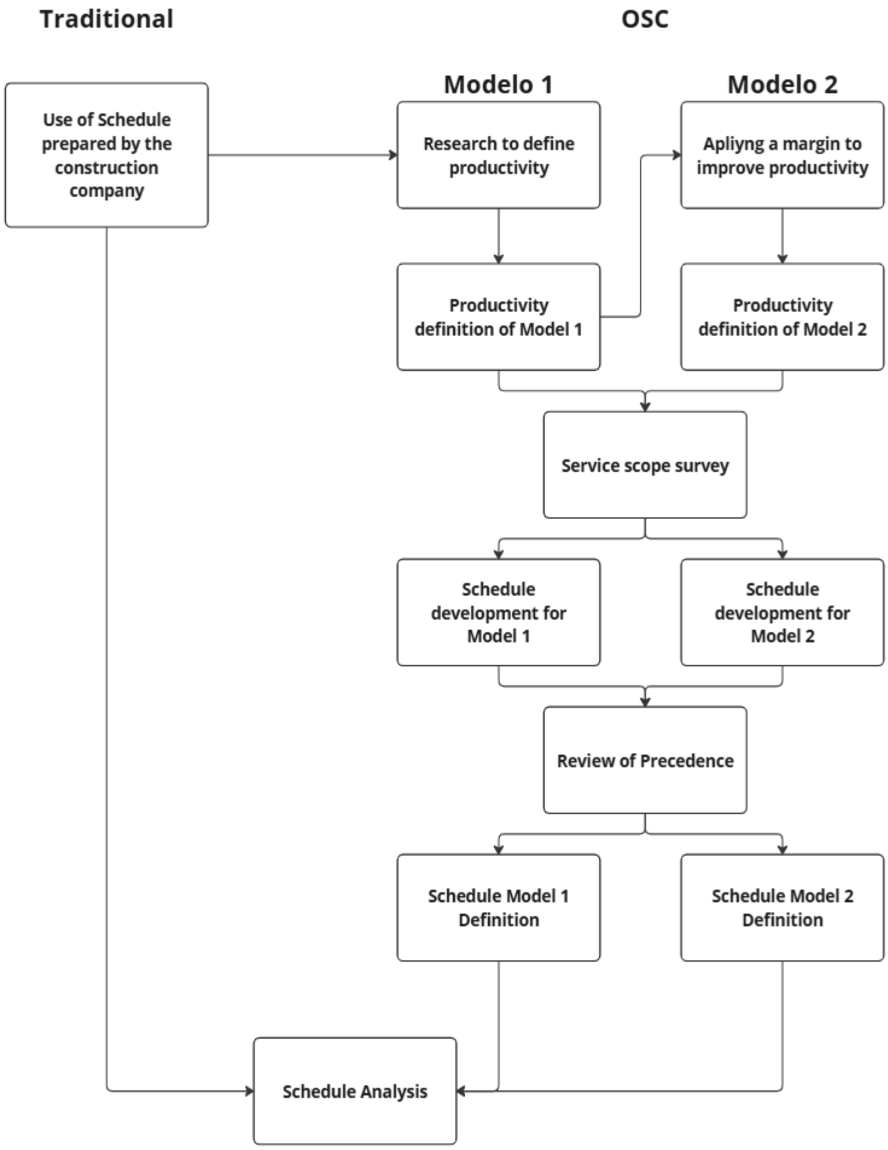


Figure 5. Schedule analysis.

2.5. Final Analysis

Multicriteria Decision Analysis (MCDA) will be implemented to compile all the information obtained and synthesize it into a single result, thus measuring the impact of the OSC method. In this study, the specific MCDA technique adopted was the Weighted Scoring Method (WSM). This method was selected over other well-known MCDA approaches such as AHP, TOPSIS, or PROMETHEE because it provides a transparent and straightforward mechanism to integrate both quantitative and qualitative results, which is especially suitable in exploratory case studies where primary stakeholder participation is limited [43]. While stakeholder engagement is a central advantage of MCDA, in this case, the weighting and scoring were assigned directly by the authors to ensure methodological consistency and comparability of the construction alternatives. Future applications of this framework may incorporate surveys or workshops with stakeholders to refine weight assignments, but the use of WSM was deemed the best fit for the scope of this research, balancing clarity, replicability, and data availability [44]. In this context, the variables will be evaluated with scores ranging from −5 to +5 to measure their impact (positive or negative). Subsequently, weights will be assigned to each variable, reflecting its importance to the project. Finally, the scores and weights for each criterion will be compiled to form an overall project impact score. To evaluate each variable, benchmarks were stated for guidance on the indication of a positive or negative result. This study chose those benchmarks. Each variable has a Grading Scale based on the chosen benchmarks to enable the final comparative analysis. The tables for each criterion are presented below.

It is important to note that BIM was used as a visualization tool and as a data-rich environment feeding directly into the MCDA process. Quantity take-offs from Revit informed us of the structural weight and cost criteria. Scheduling simulations in Microsoft Project 2021 Professional provided inputs for the schedule reduction benchmarks. Additionally, BIM-based clash detection contributed to the qualitative assessment of building design. Thus, the MCDA results presented in this study are directly underpinned by BIM-derived data, ensuring consistency between design, cost, schedule, and decision-making.

Table 1 below illustrates the grading scale for the cost analysis. The benchmark for the cost analysis was stated as a reduction of 20%. Therefore, a reduction in costs equal to or greater than 20% will represent the maximum grade in the evaluation. The grades reduce gradually according to the reduction of savings. The grades start to represent a negative impact at the moment when the costs start to increase by over 2% and the lowest grade possible is achieved if the analysis indicates an increase in costs of over 20%.

Table 1. Grading scale for the cost analysis.

Variable	Variation (%)	Grade
Cost	<−20%	5
	(−20%)–(−10%)	3
	(−10%)–(−2%)	1
	(−2%)–(2%)	0
	(2%)–(10%)	−1
	(10%)–(20%)	−3
	>+20%	−5

Similarly, Table 2 states the Grading scale for schedule analysis. The benchmark for the schedule analysis was set on a time reduction of 25% or higher. If the analysis indicates this level of savings, the project is rewarded with the maximum grade. The project can receive positive grades if the schedule reduction is at least −5%, but if there is a schedule increase of at least +5%, the project will be rewarded with negative grades ranging from −1 up to −5 if the time increase is over 25%.

Table 2. Grading scale for the schedule analysis.

Variable	Variation (%)	Grade
Schedule	≤−25%	5
	(−25%)–(−15%)	3
	(−15%)–(−5%)	1
	(−5%)–(+5%)	0
	(+5%)–(+15%)	−1
	(+15%)–(+25%)	−3
	≥+25%	−5

The analysis of the Logistical and Architectural Limitations is different from the other analyses because it is the only one that generates a more qualitative than quantitative perspective. In this regard, Table 3 represents the context in which each grade will be assigned.

Table 3. Grading scale for the architectural limitations analysis.

Variable	Variation	Grade
Architectural Limitations	Significant expansion of architectural design options	5
	Moderate expansion of architectural design options	3
	Slight expansion in architectural design options	1
	No relevant changes	0
	Light design restrictions	−1
	Moderate design restrictions	−3
	Significant design restrictions	−5

Lastly, the Structural Weight Analysis sets a benchmark for a 30% reduction in total weight, as presented in Table 4 below. As presented in the tables above, if the project manages to score a result equal to or better than the benchmark, it will receive the maximum grade possible. If it is not possible, the grade will decrease gradually until it hits the minimum if the project scores a grade equal to the opposite of the benchmark.

Table 4. Grading scale for structural weight analysis.

Variable	Variation	Grade
Structural Weight	≤−30%	5
	(−30%)–(−20%)	3
	(−20%)–(−10%)	1
	(−10%)–(+10%)	0
	(−10%)–(+20%)	−1
	(−20%)–(+30%)	−3
	≥+30%	−5

In addition to verifying the impact generated by each criterion, it is essential to present the weights that each variable should have. The choice of the weights is crucial because it can drastically change the overall result of the impact analysis. It is important to note that the choice of the weights can vary greatly depending on the project objectives and its stakeholders. After assigning weights to the variables, the final impact score is calculated by multiplying the score assigned to each variable by its respective weight, as presented in Equation (1). Figure 6 represents a flowchart that summarizes the methodology applied in the comparative analysis based on the WSM method in this article.

$$Final\ Grade = (Weight_1 \times Grade_1) + (Weight_2 \times Grade_2) + \ldots + (Weight_n \times Grade_n) \quad (1)$$

The variation ranges and weight values adopted in Tables 1–4 were not arbitrary, but are derived from a combination of references and practical considerations. The percentage thresholds (e.g., 20% for cost, 25% for schedule, 30% for weight) were defined based on two criteria: (i) benchmarks frequently cited in prior modular construction and MCDA studies as significant breakpoints in decision-making [45], and (ii) empirical values observed in the Brazilian construction market, where reductions above these margins represent a meaningful competitive advantage [46]. The small differences across parameters (20%, 25%, 30%) reflect the specific sensitivity of each criterion: cost variations above 20% are already highly impactful in feasibility decisions, whereas schedule improvements typically need to exceed 25% to be perceived as critical by developers. Weight reduction, on the other hand, becomes technically relevant when it surpasses 30%, since this is the point at which foundation systems and logistics constraints are substantially altered. The weighting system (40% for cost, 30% for schedule, 20% for architectural/logistical aspects, and 10% for weight) was aligned with current priorities in the Brazilian real estate market, where cost and schedule typically dominate project viability assessments. This study recognizes that these values may vary in other contexts and encourages future research to calibrate them using stakeholder surveys or Delphi studies to strengthen external validity [47].

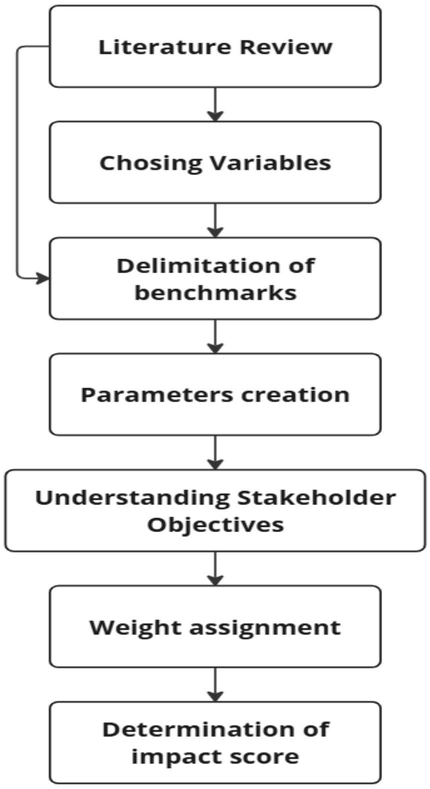


Figure 6. Weighting scoring method.

3. Case Study

The choice of the project for this case study differs from what is expected for an industrialized off-site construction study, as it is not a large, low-standard housing complex or social housing project, or even a temporary building such as a hospital or a refugee camp. The project selected for this case study was a high-standard small building with mixed usage (both residential and commercial activities). This approach was made intentionally by the authors with the aim of testing the effectiveness of the OSC in different scenarios.

Even with less affinity with the off-site construction standards, such as standardization and replication of activities in comparison with the type of projects listed above, this project was selected because it also presented some of the qualities needed for the implementation of the OSC method. The architectural project indicates a fertile field for improvement on the modularization of the dimensions and standardization of the floor with minor changes.

This building consists of a single 8-story tower divided into: ground floor, mezzanine, technical floor, four standard floors, and a rooftop. The commercial part of the development is located on the ground floor and the mezzanine, while the remaining floors are for residential use. The original project presents a deep foundation system, a reinforced concrete superstructure, and enclosures with ceramic blocks.

The project built area of the case study is presented in Table 5. The four standard floors present a high standardization level because of the similarities and the high geometrical shape of the apartments. The apartments are divided into only two types of architectural plans, simplifying the construction process. On the other hand, the other floors present lower levels of standardization, which can compromise the study results. Although the standardization on the other floors is not the most appropriate, the standard floor can compensate for this, as it represents more than 58% of the construction area of the project.

Table 5. Case study project built area.

Level	Total Construction Area (m^2)	Percentage of the Total Area (%)
Ground	290.04	19%
Mezzanine	121.82	8%
Typical (1st to 4th)	891.88	58%
Rooftop	222.97	15%

The BIM model developed for the case study project is presented in the Supplementary File. The model provided detailed architectural visualization and facilitated the modularization process, allowing the identification of standard floor layouts and façade components. The use of BIM was essential to integrate the project design and logistical aspects at an early stage, ensuring compatibility before the manufacturing of the components.

In addition to the architectural model, BIM environments were used throughout the study to generate 3D simulations of construction sequences. While these visualizations were essential in guiding the analysis of feasibility and design adjustments, this study reports their outcomes in a descriptive and analytical form rather than reproducing all intermediate graphical outputs. Specifically, BIM-derived simulations supported the evaluation of structural weight, cost, and scheduling scenarios, ensuring consistency between design constraints and the comparative results presented in this study.

3.1. Case Study Project Limitations

As mentioned in the literature review chapter, the construction method discussed in this article already brings some limitations and complications for the project. However, the case study itself also presents some characteristics that implement more complication factors that may be barriers to its construction; such characteristics will be addressed below. The three main factors contributing to complications for the case study are the limited site area, the need to maintain the original façade of the first two floors from the previous building, and the limited availability for loading and unloading materials.

The most significant factor is the site area because of its impact on the logistics and management of the project on site. The construction site is only 290 m^2, making it difficult to receive and store materials, manage movement within the construction site, and affect on-site activity management.

Furthermore, adding to the need to maintain the original façade of the previous building increases the difficulty of the construction, not only due to logistical issues, but also by adding the need for new construction activities, affecting the project costs and timelines. Preserving the façade during the demolition process of the old building represents a risk that must be overcome by structurally reinforcing the façade to ensure its stability. From a logistical perspective, the façade limited access to the site to smaller vehicles. This influenced productivity due to the increased need for horizontal transport on-site and the lack of freedom to use machinery for more suitable activities, such as foundation work.

Lastly, another major complicating factor is the limited availability of loading and unloading materials due to the urban zone where the construction site is located. This, in addition to the last two factors listed above, impacts the project financially because it forces the team to purchase materials in small quantities, leading to a loss of competitiveness in material procurement, as suppliers usually set higher unit prices in these situations.

One example of the impact of those limitations in the construction process can be indicated by the foundation work done in the original project. The selection of the root pile foundation system proved to be less than ideal due to the logistical complexities mentioned above. The substantial length of the piles, along with the space required for the installation of the necessary equipment to execute the piles, together with space constraints on the construction site and material storage challenges, resulted in difficulties in piling.

3.2. Logistical Limitations

By adapting to the industrialized system, the construction processes undergo significant changes, particularly in operation, transportation, and installation processes, compared to the traditional construction methods. The change that brings the most divergence between conventional construction and the OSC is in the transportation and logistical aspects. While the logistical process in traditional construction involves moving and storing large quantities of various materials to maintain a steady stock for on-site manufacturing, the OSC approach focuses on delivering pre-assembled wall panels directly from the factory to the construction site on a just-in-time-based system.

The traditional approach offers some benefits, such as economies of scale, but has some drawbacks, such as indirect costs linked to storage facilities, supervision, depreciation, theft, and waste. Furthermore, these characteristics can hinder projects with limited storage space, as is the case in this study.

The logistical systems also differ in how the materials are transported to the construction site. In traditional construction, materials are often smaller and standardized, allowing them to be packed efficiently in bundles. In OSC, on the other hand, although the panels and modules are also standardized, they are not packed the same way due to the size of the panels and the small differences between them. This results in a reduced "useful volume" of materials shipment. Figure 7a represents the conventional freighting system involved in traditional construction projects, while Figure 7b shows the transportation of 3D Modules used in OSC. This makes clear how the first one uses more of the vehicle compared to the second one.

The logistical limitations also impact the architectural aspect of the OSC buildings. In this system, the panels and modules must be manufactured according to the capacities of the cargo truck. Since there are plenty of logistical limitations associated with the OSC system, it is crucial to develop strategies in order to minimize their impact during the implementation of the construction method. First of all, it is necessary to ensure the alignment among all the teams involved in the manufacturing and assembly of the structures. The collaboration of those teams using the Just In Time (JIT) framework to prioritize tasks in the correct order.

(**a**)

(**b**)

Figure 7. Conventional construction transportation systems and OSC transportation systems. (**a**) Conventional construction transportation systems. (**b**) OSC transportation systems.

One example of this collaboration and coordination is the development and implementation of the "installation plan", a guideline that provides comprehensive instructions for all stages of the OSC process (production, transportation, and installation). This document helps teams to align their processes to the proper sequence of activities needed in the stages of construction. Deviations from this ideal process can lead to setbacks that promote higher costs, larger schedules, and lower efficiency.

3.3. Modifications to the Construction Process

To adapt the construction of the building analyzed in the case study to the off-site industrialized construction model, it was necessary to modify some of the initially designed construction processes and solutions. This chapter describes all the adaptations made, their justifications, and the impacts observed on the final design.

The first relevant modification is to the foundation system. On the original project, the foundation consisted of a deep foundation with cast-in-place piles; on the OSC model, the option was a raft slab foundation. Even though both options are on-site processes, the second one presents many benefits compared to the first. Firstly, the raft foundation system demands less space for its execution, something that is very important for this project in particular. Other than that, it is also a simpler and less expensive solution, generating benefits for cost and schedule reduction. However, its adoption is only viable due to the significant reduction in the weight of the building, which is a result of the changes to the enclosures and the superstructure presented below.

The main transformation occurs precisely on these two fronts: replacing the reinforced concrete structural system and the ceramic or concrete block enclosures with a lightweight, industrial-grade system. The case study followed the traditional approach widely adopted in Brazil, characterized by a high degree of craftsmanship and significant impact on the overall cost and timeframe. In contrast, the solution proposed in this study is the adoption of the Light Steel Framing (LSF) system.

LSF is a construction system that uses thin galvanized steel profiles to compose structural and non-structural elements. The most commonly used elements are structural wall panels, although the system also allows for the construction of slabs, roofs, and other components. The adoption of LSF aims to enable the construction of elements off site, adapting the project to the physical constraints of the terrain. In addition to the possibility of off-site construction, the system provides additional benefits, such as reduced building weight, lower operating costs, shorter construction times, and greater alignment with environmental guidelines. Figure 8 below shows an example of an LSF structure made for a residential property. In the picture below, it appears to be a structure assembled on-site, but this method of construction can also be adapted to off-site manufacturing and assembly.

Figure 8. Example or LSF structure for a residential project.

In Figure 9, flowcharts are displayed to demonstrate the executive processes of conventional construction and industrialized construction.

These changes, in turn, significantly impact the pre-execution process of the construction project. In the off-site model, it is essential that all designs are fully compatible and approved before component manufacturing begins. While this requirement also exists in the conventional model, the practice demonstrates greater flexibility in this format, allowing execution to begin based on partially developed designs, with adjustments made throughout the project—a very common practice in Brazil. However, this approach is not feasible in industrialized construction. Because production occurs sequentially and remotely, any incompatibilities or interferences identified late can lead to production shutdowns, the loss of already manufactured components, or the need for rework, generating delays and additional unforeseen costs. Therefore, the success of off-site construction directly depends on meticulous planning and excellence in the design phase. In Figure 10, flowcharts are displayed to demonstrate the pre-executive processes of conventional construction and industrialized construction.

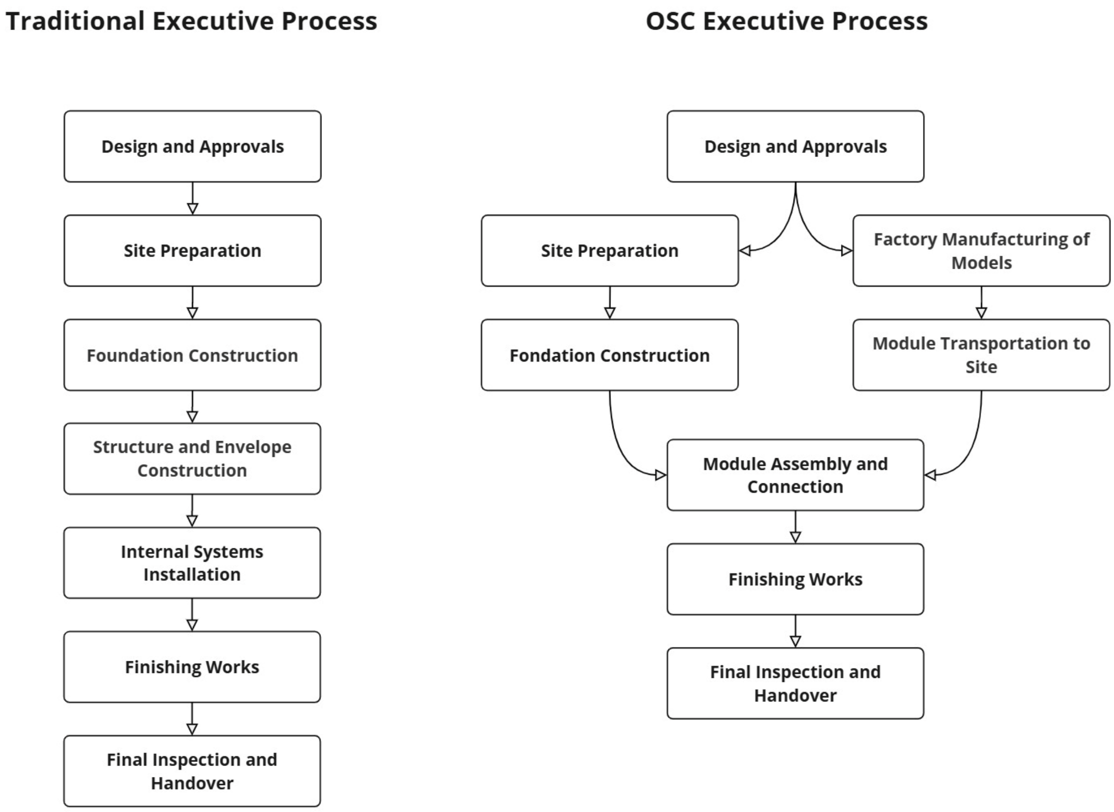


Figure 9. Comparison between traditional and off-site construction executive processes.

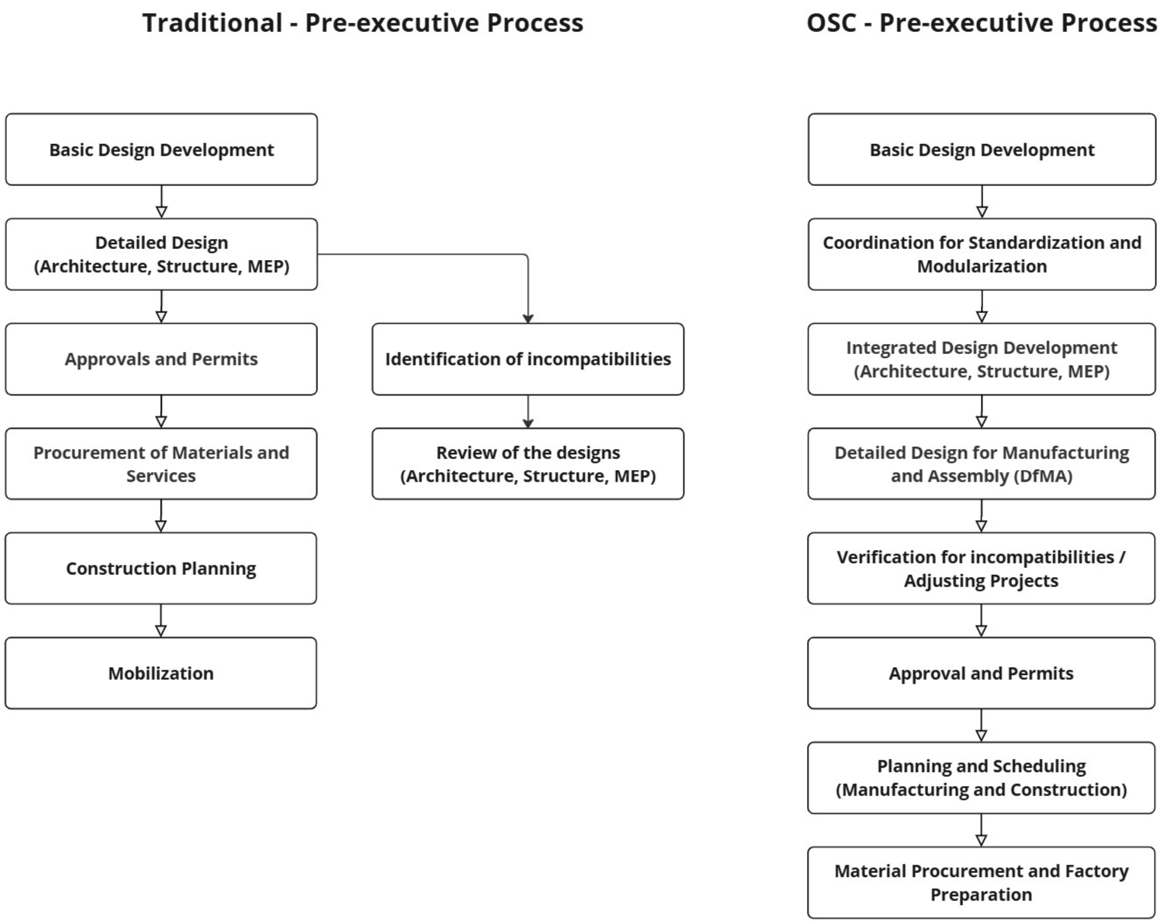


Figure 10. Comparison between traditional and off-site construction pre-executive processes.

4. Results and Discussion

The literature review indicated that modular off-site construction is an innovative construction method that can bring benefits and significant competitive advantages to the stakeholders involved. Of the benefits mentioned, the main impact is the reduction of costs and deadlines, which are common issues in the Brazilian and global real estate markets.

However, this article aims to conduct a more detailed analysis of this impact, seeking to qualitatively and quantitatively evaluate the benefits mentioned in the theoretical reviews practically. Furthermore, the project chosen to be the case study brings another important perspective on the topic, since it deviates from the traditional option. This allows not only the impact of modular construction on the parameters listed in the methodology to be verified, but also the flexibility of methods in different contexts. The results obtained from the analysis of the case study used the parameters previously listed in the methodology chapter. Next, an integrated assessment of the overall impact of adopting off-site modular construction on the project in question will be conducted.

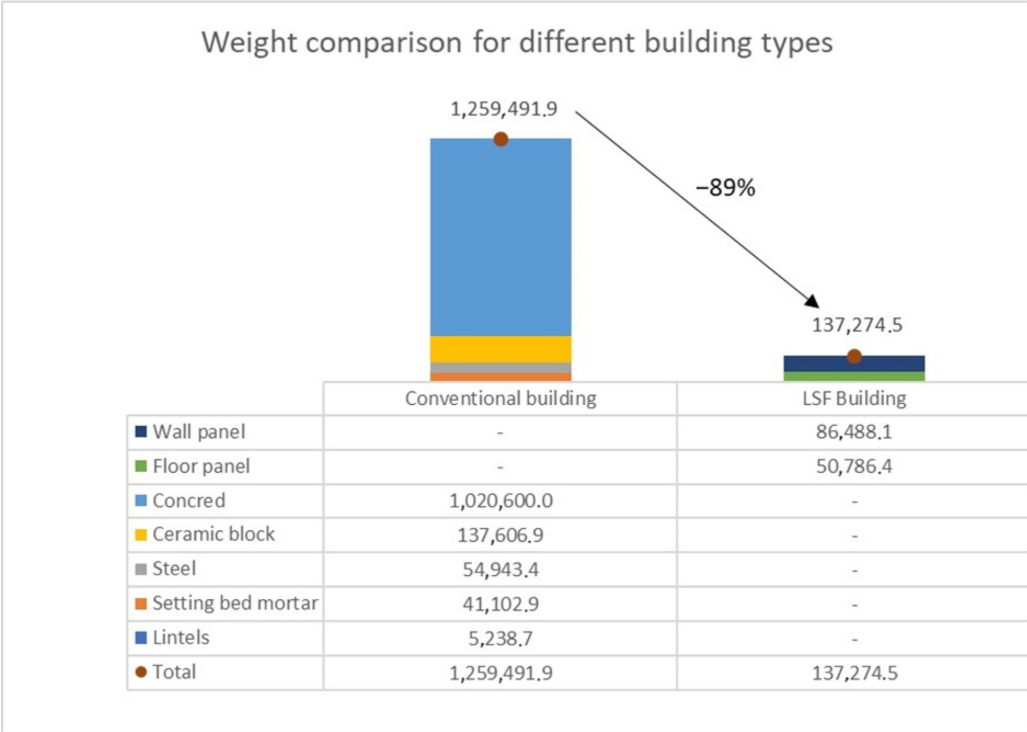
4.1. Construction Material Weight Analysis

Initially, to carry out the comparison, it was necessary to survey the materials needed to carry out the construction in both methods. For the traditional construction method, the authors utilized datasets provided by governmental sources such as the SINAPI database and official information from the agencies linked to government-based organizations in Brazil. On the other hand, to estimate the weight on the OSC method, when the information needed was not found on the datasets listed above, sources such as private companies were consulted. The integration of BIM into the modeling process facilitated this comparative analysis by providing a consistent digital environment for quantifying materials in both scenarios.

While conventional construction has structure and seals composed of various materials, such as concrete, ceramic blocks, steel, cement, and sand for subflooring, etc., steel framing-based construction has a considerably simpler list of materials, focused mainly on light steel structures and panels that function as seals for both floors and walls.

The results obtained guarantee an 89% reduction in the total weight of the structure when replacing the construction system. Figure 11 graphically illustrates the comparison between the weight of the structures and how each of the materials listed above impacts the total weight of the building. It is important to emphasize that this 89% reduction in structural weight, although significant, has been carefully verified against both the material quantity take-off generated by the BIM models and reference values from governmental databases (SINAPI) and suppliers. Similar magnitudes of weight reduction have been reported in previous studies when replacing reinforced concrete systems with light steel framing or other lightweight modular systems. For instance, Liew and Chua [8] describe comparable reductions in high-rise modular systems due to the substitution of concrete with lightweight steel modules. Likewise, Baú and Oviedo-Haito [6] observed substantial weight decreases in Brazilian modular projects using 3D steel modules. Therefore, the observed reduction in this case study aligns with evidence found in the literature, particularly in contexts where conventional reinforced concrete is replaced by industrialized light steel solutions. Nonetheless, this work acknowledges that weight reduction outcomes are highly case-specific and may vary depending on building scale, typology, and design constraints.

The indicated weight reduction has a positive impact on the project. It simplifies the necessary foundation system, leading to cost and time savings. These reductions are even more significant when we consider that the foundation is one of the only services performed on-site, thus representing part of the critical path of the project schedule.



	Conventional building	LSF Building
Wall panel	-	86,488.1
Floor panel	-	50,786.4
Concred	1,020,600.0	-
Ceramic block	137,606.9	-
Steel	54,943.4	-
Setting bed mortar	41,102.9	-
Lintels	5,238.7	-
Total	1,259,491.9	137,274.5

Figure 11. Comparative graph of the weight of the structure between the different construction methods.

4.2. Cost Analysis

For the cost analysis evaluation, the authors compared the original budget documentation associated with the project with a second budget document developed by the authors that represents the modifications needed to implement the OSC system. The OSC cost is estimated utilizing different sets of data, ranging from the UPCs provided by the SINAPI database to UPCs provided by different authors published in other articles on the topic. In some cases, when it was not possible to find information in the databases cited above, the authors produced their own UPCs. This occurred mainly due to the innovation of the construction method presented and its low adoption in Brazil. Furthermore, the new cost estimator adds items not listed on the original budget to replicate the reality of the industrialized construction method, such as a more complex and expensive logistical operation.

This cost analysis only indicates the comparison between services that are directly related during the proposed change of construction method. Therefore, it compares costs related to foundations, superstructures, and seals, but does not address topics such as finishes, among others.

While the original budget for conventional construction included an initial investment of R$ 1,871,486.76, the budget for the innovative methodology indicated an investment of R$ 1,435,871.65, representing a 23.3% cost reduction. However, it is important to emphasize that the above comparison only evaluates items that directly differ from the methodology change, excluding items that will be common costs for both projects. Therefore, when evaluating the cost reduction relative to the total project cost, this value drops to 6.18%, a considerable drop but still a significant cost reduction.

Tables 6 and 7 provide a breakdown of the two budgets. Table 6 replicates the original budget developed by the construction firm, focusing only on the items relevant to the comparison analysis. On the other hand, Table 7 breaks down the costs estimated by the authors for the implementation of the OSC method.

Table 6. Original budget of the work for structure and masonry services.

Item	Description	Unit	Quantity	Unit Price	Total
4	**Structure**				
4.1	Concrete technological control	Budget	1.00	R$ 10,000.00	R$ 10,000.00
4.2	Equipment and tools	Budget	1.00	R$ 8520.00	R$ 8520.00
	Structure—From ground floor to roof				
4.3	Concrete 35 MPa	m^3	425.25	R$ 590.00	R$ 250,897.50
4.4	Concrete formwork	m^2	2664.75	R$ 164.45	R$ 438,218.14
4.5	Formwork for exposed concrete	m^2	669.24	R$ 218.23	R$ 146,048.25
4.6	Shoring	m^2	1150.00	R$ 28.00	R$ 32,200.00
4.7	Reinforcement	Kg	54,943.35	R$ 9.28	R$ 509,874.29
4.8	Concrete stairs	Budget	1.00	R$ 74,613.70	R$ 74,613.70
6	**Masonry and partitions**				
6.1	Masonry in ceramic block 9 × 19 × 29—Internal masonry	m^2	177.28	R$ 73.63	R$ 13,053.13
6.2	Masonry in ceramic block 14 × 19 × 29—External and between-unit masonry	m^2	1481.43	R$ 101.43	R$ 150,261.44
6.3	Counter wall with 90 mm studs in Drywall—Bathroom shafts	m^2	28.27	R$ 111.08	R$ 3140.23
6.4	Conter wall with doors and windows	ml	21.32	R$ 116.00	R$ 2473.12
6.5	Lintels for internal doors and windows	ml	145.52	R$ 58.30	R$ 8483.82
9	**Finishes**				
9.1	Plaster and render for walls	m^2	3207.21	R$ 69.75	R$ 223,702.90
				Total	**R$ 1871,486.51**

Table 7. Budget of the work for structure and masonry services using LSF.

Item	Description	Unit	Quantity	Unit Price	Total
4	**Structure (slabs)**				
	Steel frame for slab	m^2	1451.04	R$ 233.52	R$ 338,846.86
	Thermal and acoustic insulation	m^2	1451.04	R$ 122.56	R$ 177,839.46
	Installation of polyethylene sheet	m^2	1451.04	R$ 49.04	R$ 71,159.00
6	**Masonry and partitions**				
	Steel frame with plasterboard and cement board closure	m^2	906.11	R$ 259.27	R$ 234,927.14
	Steel frame with plasterboard closure (both sides)	m^2	1496.14	R$ 192.35	R$ 287,782.53
	Steel frame with cement board closure (both sides)	m^2	68.83	R$ 326.19	R$ 22,451.66
	Thermal and acoustic insulation	m^2	2471.09	R$ 122.56	R$ 302,856.79
				Total	**R$ 1435,863.44**

The budget presented in Table 6 does not show great homogeneity between the items listed, since the structure item represents 77% of the total cost.

However, the budget shown in Table 7 balances the distribution of costs between items better.

Figure 12 provides a more visual comparison between the two cost estimates. As previously mentioned, the cost of the conventional structure stands out, representing more than double the cost estimated for the same item in the OSC budget. Although the estimated cost for the enclosures in the OSC model is considerably higher than that estimated for conventional construction, it does not come close to bridging the gap created by the structure cost. The direct cost reduction between the two models is equivalent to R$ 435,623.07, highlighting a 6% cost reduction compared to the total cost of the case study project (finishing, carpentry, installations, etc.).

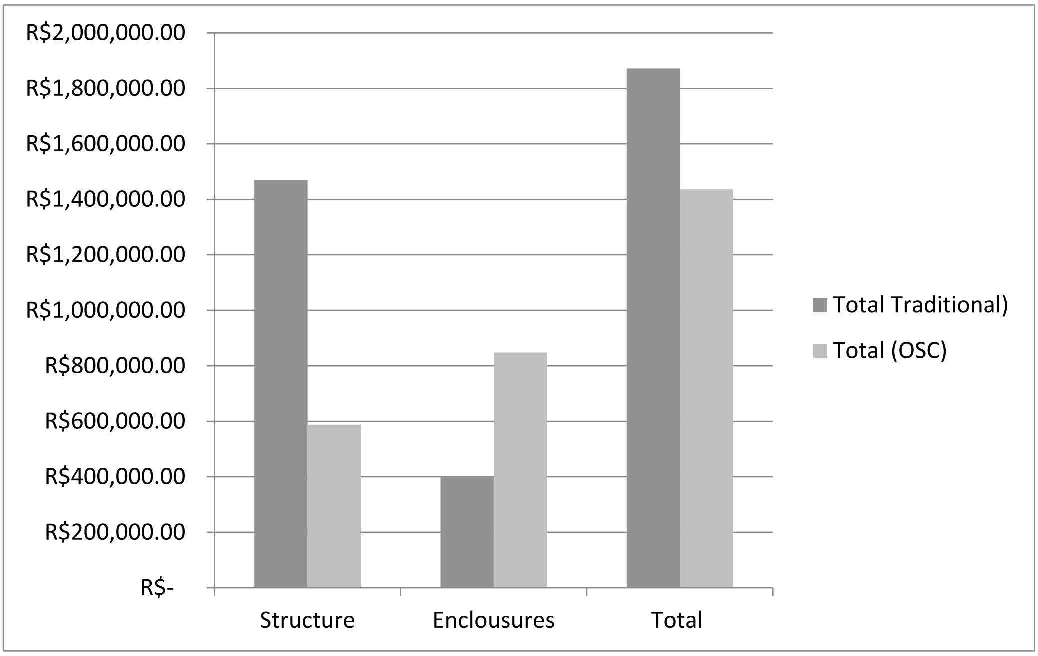


Figure 12. Comparative cost chart for each construction method.

4.3. Schedule Analysis

The timeline analysis of the project, as indicated in the methodology, compares the schedule initially associated with the project with two different schedules. One represents Model 1, where prefabrication involves only the panel structure, with the remaining structural assembly and installation services to be performed on-site. The other, Model 2, represents a higher degree of prefabrication, where all panel fabrication occurs off-site, with only installation remaining at the construction site. Model 1 is the most common in Brazil, while Model 2 maximizes the positive impacts of construction methods, being the method initially implemented outside the country. The productivity for Model 1 was set at 250 m^2/day, based on data provided by companies specialized in the partially industrialized method. As it was not possible to find reliable data about the productivity of Model 2, the author adopted an increase of 50% in comparison to Model 1, setting the productivity of Model 2 at 375 m^2/day.

BIM were particularly useful in validating the schedule comparisons, as they enabled visualization of how prefabricated modules would be assembled on-site versus traditional sequential construction. The original schedule determines the total project deadline at 287 working days, of which 95 days are for the execution of the structure and enclosures, and 128 days if we include services such as building installations, window and door installations, etc., in addition to the structure and enclosures. Model 1 presents a solution for modifying structural and enclosure services. With the estimated productivity, this model can complete these services in 17 days. This represents a 78-day reduction in turnaround time, equivalent to a 27% reduction in the project timeframe.

Model 2, on the other hand, provides a solution that allows for the modification of not only the structure and seals but also the inclusion of prefabrication in the installation services, frame installations, and eventually even finishing. With estimated productivity, this model sets the need for only 12 days of on-site activities. Therefore, this represents up to a 116-day reduction in the schedule, equivalent to a 40% reduction in the project time frame. It is important to note that the time saved between Models 1 and 2 is not only due to the five fewer days of on-site service provided by Model 2, but also due to the capacity of this Model to include a wider range of activities to be carried off-site, simultaneously with the activities that need to be done on-site, thus maximizing time savings.

Table 8 indicates the timeframe for the installation of the panels according to the Model 1 method. Its columns represent the area of each level of the building and the time needed to install the panels on each respective floor according to the productivity expected. Table 9 represents a similar timeframe, but according to the Model 2 method; the only difference between each table is the productivity expected.

Table 8. Representation of the timeframe for panel installation in Model 1.

		Walls Panels	
	Area (m^2)	**Productivity (m^2/Day)**	**Required Days for Execution**
Ground floor	427	250	1.8
Mezzanine	234	250	1.0
Technical floor	112	250	0.5
1st floor	385	250	1.6
2nd floor	385	250	1.6
3rd floor	385	250	1.6
4th floor	385	250	1.6
Rooftop	184	250	0.8
Roof	44	250	0.2
		Slab Panels	
	Area (m^2)	**Productivity (m^2/day)**	**Required days for execution**
Ground floor	0	250	0.0
Mezzanine	138	250	0.6
Technical floor	87	250	0.4
1st floor	208	250	0.9
2nd floor	208	250	0.9
3rd floor	208	250	0.9
4th floor	208	250	0.9
Rooftop	208	250	0.9
Roof	55	250	0.3
Total days required in Model 1			**16.5**

Table 9. Representation of the timeframe for panel installation in model 2.

		Walls Panels	
	Area (m^2)	**Productivity (m^2/Day)**	**Required Days for Execution**
Ground floor	427	375	1.2
Mezzanine	234	375	0.7
Technical floor	112	375	0.3
1st floor	385	375	1.1
2nd floor	385	375	1.1
3rd floor	385	375	1.1
4th floor	385	375	1.1
Rooftop	184	375	0.5
Roof	44	375	0.2
		Slab Panels	
	Area (m^2)	**Productivity (m^2/day)**	**Required days for execution**
Ground floor	0	375	0.0
Mezzanine	138	375	0.4
Technical floor	87	375	0.3
1st floor	208	375	0.6
2nd floor	208	375	0.6
3rd floor	208	375	0.6
4th floor	208	375	0.6
Rooftop	208	375	0.6
Roof	55	375	0.2
Total days required in Model 2			**11.2**

Table 10 initially shows the estimated time for completing the activities in the original schedule. Furthermore, it shows not only the estimated time for completing the same activities in models 1 and 2, but also the percentage of time reduction achieved due to the change in the execution process. This table serves as a summary for the time reduction in both scenarios, indicating the potential benefits brought by the OSC method in these criteria.

Table 10. Summary of the reduced deadline due to the introduction of the OSC.

	Time (Days)	
Enclosures and Superstructure (Original)	95	
Building Installations and Frame Installation (Original)	33	
Total Project (Original)	287	
	Time (Days)	Deadline Reduction (%)
Enclosures and Superstructure (Model 1)	17	82%
Total Project (Model 1)	209	27%
	Time (Days)	Deadline Reduction (%)
Enclosures, Superstructure, Building Installations, Frame Installations (Model 2)	12	91%
Total Project (Model 2)	171	40%

4.4. Architectural Limitations Analysis

Analyzing the case study project around its architectural limitations proved to be more complex than the other variables since it has more qualitative than quantitative parameters. In this regard, without quantitative parameters, the authors listed the necessary alterations needed in the case study project in order to adapt it to the OSC standards, and compared it to the grade system listed in the methodology chapter.

Since the first project analysis, it is possible to see a strong convergence between the building layout and the concepts of modular construction. The floors are composed of highly geometrical low-complexity plans, an important factor that simplifies the efforts of standardization of the project.

Despite that, the modularization of the dimensions of the partitions would still be needed in this project. This process is important to reduce the material waste and optimize labor both on- and off-site. Even with the modularization process, the impacts on the actual architectural layout are minimal, mainly because of the existing standardization level of the project.

Despite not being a major problem in this case, the architectural limitations would be more complex in two main scenarios: first, in projects with a low initial level of standardization, where major architectural changes would be necessary, disrupting the architectural concepts that were initially designed; second, in projects where there are design changes at the same time as the production of the structures, thus compromising the manufacturing stages due to revisions or lack of information.

Given the conditions explained above, it is understood that, largely due to the specific conditions of the case study project, the limitations arising from the executive change are minimal. Even if they exist, the changes will be barely noticeable, becoming complications only in exceptional cases, and therefore not considered in this study. For this reason, we consider the architectural limitations to be “minor,” representing a score of -1 in this study.

4.5. Final Analysis

After evaluating the case study according to the variables listed in the methodology chapter, it is possible to apply the Weighted Scoring Method (WSM) formula to obtain a more well-rounded perspective of the impact of the OSC method on the case study project. This study assigned weights for each criterion based on the perceived priority among these parameters in a Brazilian construction market scenario. For a more universal approach, it would be important to conduct field research with a sample size focused on experts in the field to more accurately capture the importance of each of these parameters. The weights assigned for cost reduction, schedule reduction, architectural limitations, and weight reduction were 40%, 30%, 20%, and 10%, respectively.

The grades obtained during the case study were as follows: The highest grades were given to the parameters of weight reduction and time reduction. In both cases, the analysis indicates a result considerably better than the benchmark, being awarded the maximum grade in both variables. Cost reduction, despite presenting a positive result, could not possibly come close to the benchmark, resulting in a +1 grade. Finally, the only negative grade was given in relation to the architectural limitation variable. The slight restrictions implemented during the design process resulted in a -1 score for the case study.

After applying the formula that takes into account both scores and weights, it is possible to reach some conclusions. The highest overall score was given to the deadline reduction parameter, which suggests that for projects where deadlines are one of the most important factors, OSC is a highly recommended solution. Other than that, the cost reduction and the weight reduction showed similar impacts on the case study. It shows that while the weight reduction reached its fullest potential, the cost reduction still has room for improvement, which could generate an even more positive impact when comparing OSC to traditional construction. The architectural limitations do not show an immense impact in this case study, but it is important to note that, if the project was less suitable for the modular concepts or if the importance of respecting the original architectural design was not negotiable, it would highly compromise the overall score of impact obtained in this research. Table 11 shows the weighting of each of the scores obtained for the criteria analyzed. Therefore, the project in question presented a positive impact rating of 2.2. This score indicates a very positive result for the OSC implementation.

Table 11. Consideration of final grades for the degree of impact on the case study project.

Variable	Weight	Grade	Grade × Weight
Cost	0.4	1	0.4
Schedule	0.3	5	1.5
Architectural Limitations	0.2	−1	−0.2
Structural Weight	0.1	5	0.5
			2.2

Beyond structural weight, costs, and schedule, the results also carry implications for broader sustainability dimensions. The reduction in structural mass translates into a simplified foundation system and into a substantial decrease in embodied carbon, since concrete and masonry are among the highest contributors to construction-related emissions. By shifting to lightweight steel framing and prefabricated elements, material waste is minimized, and off-site precision manufacturing reduces energy consumption during the construction stage. Over the entire lifespan of the building, the modular components can support circular economy principles, enabling disassembly and recycling. From an economic sustainability perspective, while this study quantified only immediate cost reductions, modular construction can further enhance long-term value through lower operational energy demand (due to improved envelope performance and insulation) and potential return on investment from faster project delivery. These advantages also have implications for affordability and scalability, as reduced construction time and waste can lower entry barriers for developers and potentially broaden access for residents in future applications.

5. Conclusions

This article presents an analysis methodology applied in the comparison between the use of industrialized construction concepts and conventional construction to evaluate whether the impact of replacing the construction methodology is a good solution for replacing traditional methods of construction and a good overall alternative for the future of the construction sector.

In the analysis, which considered a case study based on a real project, the replacement presented a considerably satisfactory result, achieving a score of 2.2 on a scale ranging from −5 to +5, demonstrating that off-site construction can be a more efficient alternative. The positive impact is primarily due to the results obtained in terms of reduction in cost and time, which combined result in over 90% of the grade received in the global analysis.

Although the score for cost reduction was the highest, the main conclusion reached by the analysis revolves around cost reduction. The importance of reducing deadlines shows that for projects where deadlines are a major challenge, OSC is the ideal solution. However, analyzing the score obtained for the cost parameter reveals that this factor holds the greatest potential for improvement in the construction methodology, potentially making it even more important in the future if cost savings can be achieved. If the cost savings indicated in this case study matched the benchmarks, the total impact grade would increase by over 70%, achieving 3.8 points.

It was also noted that, in the case study analysis, some variables significantly exceeded their benchmarks. This may indicate that the benefits brought by these factors are already considerable and do not require short-term improvements. This allows researchers to focus their time and investment on other variables.

Finally, the methodology presented concludes that off-site modular construction is a suitable solution for the project in question and can generate benefits over conventional construction. Furthermore, based on the importance of the parameters chosen for this study, it is beneficial to prioritize the most impactful factors, such as cost.

In reflecting on the broader sustainability discourse, the findings of this study can also be positioned within the three pillars of sustainability. From an environmental standpoint, the significant reduction in structural weight and material demand illustrates the potential of modular systems to decrease resource consumption, waste generation, and site-related disturbances. The economic benefits were directly observed through measurable cost savings and schedule reductions, reinforcing the competitiveness of industrialized solutions in the Brazilian construction market. Finally, while this research did not explicitly quantify social outcomes, off-site modular approaches may offer relevant social benefits, such as improved worker safety through controlled factory conditions, reduced noise and disruption in dense urban areas, and faster delivery of high-quality housing and mixed-use buildings to meet community needs. These aspects highlight the contribution of modular construction not only to project-level efficiencies, but also to the wider sustainability agenda, while underscoring the importance of future research dedicated to more systematically evaluating its social impacts in Brazil.

During its execution, this study identified points where there is room for improvement and which may encourage more complete, accurate future studies. The first way that future research can improve upon this research is by setting the variables on which the study analysis must focus. While this article had the variables selected directly by the authors based on field experience, the most accurate way of setting these variables can be done by applying field research with multiple professionals from different parts of the world. This can provide a more global perspective of the comparison and generate different conclusions.

Furthermore, another way to draw more conclusions with this methodology is by repeating the process executed in this article with different case studies. This can enrich the research from two different perspectives: it can further strengthen the thesis defended in this article by ensuring a greater number of methodology tests, and it can introduce a project analysis that can provide the exact characteristics of a project that contribute to a better use of the industrialized construction solutions.

Another improvement that can be made is to introduce a quantitative way to measure the architectural limitations on the output of the project. By adding quantitative parameters to this analysis, it will be easier to apply this methodology in other case studies without variation of judgment between authors. Additionally, the decision-making framework applied in this study relied on the Weighted Scoring Method (WSM). This choice was made because it is simple, transparent, and replicable, allowing integration of diverse performance criteria without requiring extensive stakeholder input at this stage. Nevertheless, future studies could enrich this approach by engaging stakeholders directly to assign or validate weights, thus capturing broader perspectives.

Lastly, it would also be positive if future studies could introduce field research aiming to set the weights on the variables in a more accurate way. This field research can be done in two main ways: either through more generic research by asking professionals about the general importance of each variable for them, or in a more case-by-case perspective by asking the specific case study project management team their opinions on the importance of each criterion. It is important to highlight that the weighting system and variation ranges proposed in this study are context-specific, reflecting both the Brazilian construction market and the characteristics of the selected case study. While these thresholds allow for meaningful comparisons in this research, they are not intended as universal values. Future applications of the methodology should recalibrate the benchmarks and weights according to the priorities of local stakeholders and project-specific conditions.

Future studies should further expand the scope of sustainability assessment by incorporating detailed environmental, economic, and social metrics, as well as systematically quantifying social impacts such as labor conditions, urban disruption, and housing accessibility. Additionally, clearer articulation of the digital tools and methods applied, particularly the role of BIM-based analyses, 4D and 5D simulations, and parametric modeling, can help strengthen the reproducibility of results and their transferability to industry practice. These extensions will not only reinforce the academic rigor of future studies, but also provide practitioners with a more comprehensive framework for decision-making in modular construction projects within Brazil and other emerging markets.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17177791/s1, File S1: BIM model developed for the case study project.

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