



## ASSESSING THE IMPACT OF PREFABRICATION ON THE CARBON FOOTPRINT OF MULTI-STORY RESIDENTIAL CONSTRUCTION

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**ABSTRACT:** As sustainability becomes a global priority, the construction sector faces a significant challenge: reducing its carbon footprint while meeting the growing demand for housing. Prefabrication, a method involving the manufacturing of building elements off-site to be assembled on-site, emerges as a promising solution to achieve this goal. This approach has the potential to reduce waste and carbon footprint but also offers advantages in terms of quality and speed of execution. This work is set against a backdrop where the climate crisis demands a reevaluation of traditional construction practices. The choice of this topic stems from the imperative to find more environmentally friendly construction methods. Specifically, this research aims to assess the impact of prefabrication on reducing the carbon footprint in the construction sector, especially in multi-story residential buildings. Employing a mixed-methods approach, the study involved an in-depth literature review, semi-structured interviews with construction industry professionals, and a questionnaire administered to a prefabricated construction company in Quebec. The research also evaluated the Gestimat digital tool for environmental assessment of building materials. Data analysis involved thematic evaluation of qualitative inputs from interviews and the questionnaire, as well as a comparative assessment of prefabrication's environmental performance across different life-cycle stages. Findings indicate that prefabrication plays a significant role in reducing the carbon footprint, especially during the production and construction phases of multi-story residential buildings. However, factors such as the specific materials used, and the degree of prefabrication integration also influence the environmental impact. Despite its potential, widespread adoption of prefabrication is hindered by industry inertia, misperceptions about its environmental benefits, and an underestimation of its potential. This research highlights the need for targeted efforts to bridge the gap between the theoretical potential of prefabrication and its practical implementation in the Quebec context. Recommendations include improved communication strategies, pilot projects, and case studies to demonstrate the environmental and economic benefits of prefabrication in multi-story residential construction and accelerate its adoption towards a more sustainable built environment.

### 1. INTRODUCTION

#### 1.1 Context and Problem Statement

The construction sector is a major contributor to global greenhouse gas emissions and energy consumption, accounting for 36% of worldwide energy use and 37% of energy-related CO<sub>2</sub> emissions, as shown in the figure. This underscores the significant environmental impact of buildings and construction activities.

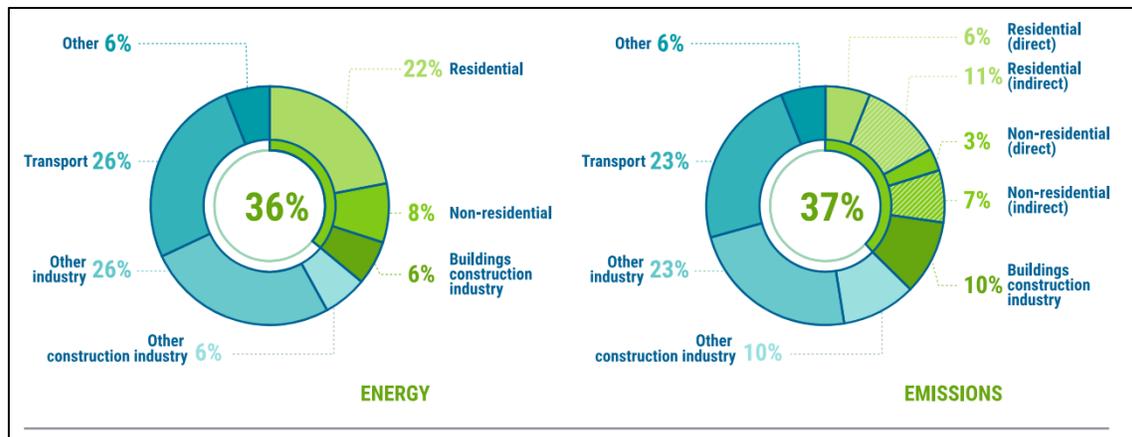


Figure 1: Contribution of Buildings and Construction Industries to Global Energy Consumption and Greenhouse Gas Emissions. Source: UNEP 2022

Multi-story residential buildings generate a significant carbon footprint due to their intensive material requirements and operational energy consumption. The growing demand for urban housing further accentuates this environmental impact, underscoring the importance of developing more sustainable construction practices (World Green Building Council, 2021).

Considering the climate emergency, many countries have implemented strict environmental regulations to reduce carbon emissions from the construction sector. For example, Canada has set ambitious GHG reduction targets, aiming for carbon neutrality by 2050. To achieve these objectives, innovative and sustainable solutions must be adopted in the multi-story residential construction sector, including low-carbon design approaches and greener construction practices (National Research Council of Canada, 2023).

## 1.2 Objectives and Contributions

This study aims to evaluate the impact of prefabrication on reducing the carbon footprint in the construction sector, particularly in multi-story residential buildings. The specific objectives of the study are:

- To analyze the carbon emissions associated with different stages of the construction life cycle, including production, transportation, and on-site assembly.
- To identify the factors influencing the environmental performance of prefabrication, such as materials used and the degree of prefabrication integration.

The study contributes to the body of knowledge by providing empirical evidence on the environmental performance of prefabrication in multi-story residential buildings. It also highlights the potential of prefabrication to reduce carbon emissions and supports its adoption as a sustainable construction practice.

## 2. LITERATURE REVIEW

### 2.1 Offsite Construction and Prefabrication

Residential construction practices have undergone a marked evolution over the years, passing from local artisanal techniques to industrialized methods, and then to technologically advanced sustainable approaches. Before industrialization, construction relied on local, natural materials such as wood, stone or clay, with low embodied energy but limited structural capacity (Bhorkar et al., 2021; Dolmatov et al., 2022). These techniques, mainly dominated by manual labor, had a low carbon impact, but a larger per capita footprint (Meyer et al., 2024).

Industrialization in the 20th century revolutionized construction methods. The urgent need for housing after the world wars accelerated the adoption of prefabrication as a quick and efficient response to labor and material shortages (Womack et al., 1990; Carbone, 2022). During this period, cement became responsible for around 5% of global CO<sub>2</sub> emissions (Al-Omari et al., 2023), and reinforcing steel accounted for between 13% and 17% of the carbon footprint of buildings (Fraile-Garcia et al., 2019; Xiaodong et al., 2014). The rise of standardized systems, notably in-situ cast concrete, has accentuated emissions during construction phases (Bhorkar et al., 2021; Abdullah & Al-Nuamman, 2023).

Inspired by industrial production chains, particularly the lean manufacturing principles developed by Toyota, the sector adopted methods aimed at improving efficiency, reducing costs and ensuring consistent quality (Womack et al., 1997). Between the 1970s and 1990s, prefabrication developed mainly for economic reasons, without integrating growing environmental concerns.

Since the 2000s, the challenges of climate change have transformed the sector's objectives. The integration of technologies such as Building Information Modeling (BIM) and Design for Manufacturing and Assembly (DfMA) has enabled more precise planning, optimized use of materials and a reduction in errors and waste (Assaad et al., 2022). These tools also facilitate accurate tracking of emissions, with case studies showing a carbon footprint of 3.2 tonnes of CO<sub>2</sub>eq per inhabitant in Montreal, and a clear difference between single-family homes 8.2 tonnes and compact units 2.0 tonnes (Meyer et al., 2024).

At the same time, the integration of life cycle assessment (LCA) has made it possible to distinguish emissions linked to the operational phase from 60 to 80% in conventional buildings (Kurian et al., 2021; Al-Omari et al., 2023), from those generated during the construction phase, 94 to 97% of which are due to the manufacture of materials (Xiaodong et al., 2014). This shift focuses on operational to intrinsic carbon highlighting the urgency of acting from the earliest stages of a project.

Faced with these facts, several solutions are emerging. Engineered wood structures can reduce emissions by 25% in denser urban environments (Meyer et al., 2024). Precast concrete systems not only speed up construction by 30% compared with traditional methods (Abdullah & Al-Nuamman, 2023). But also limit local emissions. Replacing conventional cements with CEM-II mixes also reduces emissions from load-bearing columns by 13.6% (Fraile-Garcia et al., 2019).

Prefabrication thus appears not only as an industrial innovation, but also as an essential strategy for reducing greenhouse gas emissions. Factory processes are standardized, material losses limited, and waste management optimized. This approach is a major lever for low-carbon residential construction (Abanda et al., 2017).

Despite these progresses, some challenges remain. Engineered wood vertical densification projects, if poorly planned, can increase the urban carbon footprint by 25% (Meyer et al., 2024). Differences of 15-20% remain between results obtained using automated LCA tools and manual ICE calculations (Kurian et al., 2021). Furthermore, operational emissions can be up to 40% higher in hot climates than in temperate zones (Meyer et al., 2024), highlighting the importance of contextual adaptation of solutions

Today, prefabrication is recognized as a key strategy for addressing the challenges of the construction industry, including inefficiency, excessive waste, and significant greenhouse gas emissions (Abanda et al., 2017). By manufacturing building components in controlled environments, prefabrication improves quality, safety, and working conditions while reducing costs and construction timelines. It also minimizes environmental impact by optimizing resource use, reducing waste, and decreasing carbon emissions. As urbanization continues to rise and the demand for sustainable construction grows, prefabrication offers a viable solution for efficient, high-quality, and eco-friendly building practices (Salama et al., 2021).

## **2.2 Carbon Footprint in the Construction Industry**

Globally, the construction industry plays a crucial role in environmental impact due to its high carbon footprint, which arises from both operational energy use and embodied carbon in building materials. As operational carbon decreases with improved energy efficiency and renewable energy adoption, embodied

carbon becomes increasingly significant, potentially accounting for over 90% of a building's total emissions by 2050 (CAGBC, 2022). This shift highlights the urgent need to address embodied carbon to achieve sustainable construction practices.

Greenhouse gases (GHGs), including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and fluorinated gases, trap heat in the atmosphere, contributing to global warming. CO<sub>2</sub> is the most prevalent GHG emitted by human activities, representing 79.7% of all emissions, while methane contributes 11.1% (U.S. Environmental Protection Agency, 2022). To standardize measurement, CO<sub>2</sub>-equivalent (CO<sub>2</sub>e) is used to express the impact of various GHGs in terms of the amount of CO<sub>2</sub> that would have the same global warming effect. This enables a unified approach to calculating and comparing GHG emissions across different sources (U.S. Environmental Protection Agency, 2022).

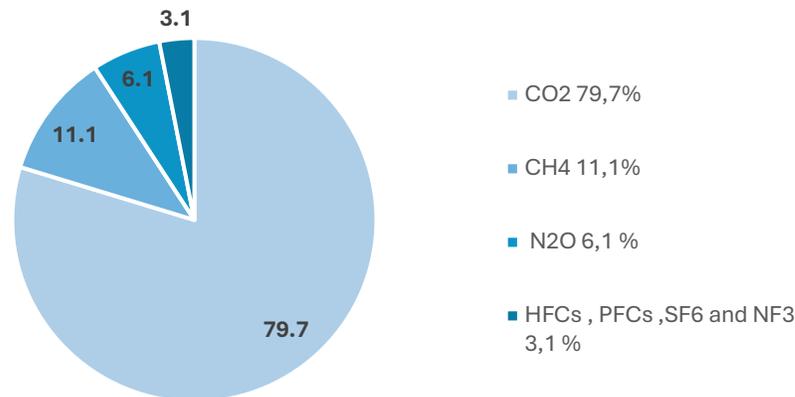


Figure 2:Quantities of GHGs emitted by type of GHG, from: Inventory of U.S. greenhouse gas emissions and sinks: 1990-2022.

Embodied carbon emissions are associated with all stages of a building's lifecycle, from raw material extraction to manufacturing, transportation, construction, maintenance, and demolition. These emissions are substantial because they are released before the building becomes operational. Therefore, reducing embodied carbon by 40% by 2030 is crucial to achieving global climate targets (World Green Building Council, 2021).

Operational carbon refers to GHG emissions resulting from the building's energy use during its operational phase, including heating, cooling, lighting, ventilation, and electrical appliances. Globally, the building and construction sector accounted for approximately 37% of energy-related CO<sub>2</sub> emissions in 2021, reaching a record high of 10 gigatons of CO<sub>2</sub>. Despite a 16% increase in investment in energy efficiency, the total energy demand for buildings grew by 4% in 2021 (UNEP, 2022). Reducing operational carbon is essential to meeting global climate goals, as these emissions account for around 28% of GHG emissions from the built environment (World Green Building Council, 2021).

For construction materials, wood, concrete, and steel are the most widely used, but they have vastly different carbon footprints. Wood is considered a sustainable option as it sequesters carbon during its life cycle and can replace more carbon-intensive materials like concrete and steel (Cecobois, 2021). Concrete is responsible for approximately 7% of global GHG emissions, primarily due to the production of cement, which involves chemical reactions and fossil fuel combustion. The Canadian cement and concrete industry are working towards achieving net-zero emissions by 2050 through innovations such as alternative fuels, improved energy efficiency, and carbon capture and storage (CSC) technologies (Roadmap to Net-Zero Carbon Concrete). Steel production accounts for 8% of global CO<sub>2</sub> emissions, largely due to its energy-intensive manufacturing process. To reduce its carbon footprint, the industry is exploring electric arc furnaces, increased recycling, and hydrogen-based reduction methods (Meyer et al., 2024).

A comparative study conducted in Montreal analyzed the material intensity and GHG emissions associated with concrete, steel, and wood in construction. The study revealed that wood significantly reduces the carbon footprint compared to concrete and steel. For instance, a wooden structure emitted 103 kg CO<sub>2</sub>e per square meter, while a similar steel structure emitted 207 kg CO<sub>2</sub>e per square meter (Meyer et al., 2024). In addition, using wood instead of conventional materials could reduce GHG emissions by 254 tonnes of CO<sub>2</sub>e, equivalent to removing 200 cars from the road for a year (Cecobois, 2021).

## **2.3 Comparison of Construction Methods**

Prefabrication often results in lower GHG emissions compared to traditional on-site construction. According to a 2009 study, modular construction compared to on-site construction saves 55% of planning time and reduces CO<sub>2</sub> emissions by 43%. The study conducted by Al-Hussein (2009) revealed that conventional construction methods require 14.3 months for completion, resulting in 98.9 tonnes of CO<sub>2</sub> emissions. In contrast, modular construction reduces this duration to only 6.3 months and leads to lower emissions of 56.3 tonnes of CO<sub>2</sub>.

Further studies by Kouhirostami and Chini (2022) indicate that modular construction, which involves manufacturing components or entire buildings in a factory before transporting them to the site, can lead to significant reductions in carbon emissions. For example, it has been shown that prefabricated modular buildings reduce GHG emissions by up to 47% compared to conventional construction methods.

Comparative studies have shown that prefabrication can reduce carbon emissions by up to 28.8% compared to traditional methods, owing to optimized production processes and waste reduction. Moreover, the use of BIM enhances the efficiency of prefabrication by facilitating detailed planning, precise material utilization, and optimized logistics, which in turn lowers CO<sub>2</sub> emissions related to transportation (Wong & Fan, 2013).

## **2.4 Carbon Impact assessment**

Life Cycle Analysis (LCA) is the most widely used method for assessing the environmental impact of construction methods throughout their life cycle, from material extraction to the end-of-life of a building (ISO 14040, 2006). In this study, Gestimat, a digital platform developed by Cecobois in collaboration with CIRAIG, is utilized for the environmental evaluation of construction materials. Gestimat enables a detailed assessment of carbon emissions at various stages of the life cycle, including production and transportation (CIRAIG, 2020).

Gestimat employs an emissions database to model different construction scenarios and to compare the environmental impact of each one. This approach facilitates informed decision-making toward more sustainable construction practices (Cecobois, 2022).

## **3. METHODOLOGY**

The research adopted a mixed-methods approach, combining qualitative methods through 3 questionnaires and 2 semi-structured interviews, as well as quantitative methods, to ensure comprehensive data collection and analysis.

The data collection process began with a detailed document analysis aimed at comparing theoretical findings from existing literature and previous studies with practical observations from the construction industry. These observations were gathered through questionnaires and interviews conducted with professionals in the construction field. Additionally, technical documents, construction reports, and environmental databases were analyzed to obtain quantitative data on GHG emissions related to prefabricated building components. However, this phase was constrained by limited data availability and challenges in obtaining participation from industry stakeholders, which affected the continuation of the study on the impact of prefabrication, along with time constraints.

Qualitative data were collected through 2 semi-structured interviews with construction industry professionals, providing in-depth insights into their perceptions, experiences, and opinions regarding prefabrication. This approach enabled a nuanced understanding of industry attitudes toward sustainability and the environmental benefits of prefabrication.

#### 4. DATA ANALYSIS

The current literature shows diverse perspectives on the impact of prefabrication on the carbon footprint of multi-story residential construction. This variability is due to the different methods used by researchers to quantify and evaluate this impact, depending on factors such as the degree of prefabrication and the various life cycle phases considered. Some studies focus on specific prefabricated components rather than the entire building, making it challenging to accurately quantify overall CO<sub>2</sub> emissions and potentially leading to results that do not reflect the total impact.

To illustrate these methodological differences and the findings obtained, table 1 below compiles data from various studies in literature. Each study evaluates the impact of prefabrication based on different factors, including building type, degree of prefabrication, and specific life cycle phases. The results indicate CO<sub>2</sub> reductions ranging from modest to significant, highlighting the potential effectiveness of prefabrication depending on the context and specific applications.

Despite the evidence of significant CO<sub>2</sub> emission reductions through prefabrication, these environmental benefits are often not recognized within the industry, where economic considerations dominate decision-making. This gap between academic findings and industry recognition suggests a disconnect between theory and practice, exacerbated by ineffective communication of environmental benefits beyond immediate cost savings.

To move forward, it is essential to develop a standardized and consistent methodology for evaluating the carbon footprint of prefabrication, encompassing all life cycle stages and related carbon emissions. This would allow for more reliable comparisons between studies and a better understanding of the true benefits of prefabrication. Additionally, it is necessary to highlight the qualitative benefits of prefabrication, such as improved construction quality and reduced project timelines, which are often overshadowed by cost-focused discussions.

Table 1: Comparison of the Environmental Impact of Prefabrication on Reducing CO<sub>2</sub> Emissions, Waste, and Energy Consumption in the Literature. (Author, 2024) / N/C: stands for Non-Calculated or Cited

Reference	Country	Building Type	Prefabrication Type	Project Phases	CO <sub>2</sub> Reduction (%)	Waste Reduction (%)	Energy Reduction (%)
Zhang, X., & Wang, F. (2016)	China	Residential	N/C	A1 to A3	Yes, N/C	No, N/C	No, N/C
Brege et al. (2014)	Sweden	Multi-story residential buildings	Prefabricated wooden structures, modular elements	A1 to A5	Yes, N/C	No, N/C	No, N/C
Pal et al. (2017)	Finland	Townhouse	N/C	A1 and B1	No, N/C	No, N/C	50 (GSHP)
Kouhirostami, M., & Chini, A. R. (2022)	United States	Residential	Modular construction	A1 to A3/A4/A5	47/ 8/ 43	Yes, N/C	Yes, N/C
Padilla-Rivera, A., & Blanchet, P. (2017)	Canada	Multi-story residential buildings	Prefabricated wooden structures	A1 / A4 / A5	48	No, N/C	No, N/C
Du, Q., Bao, T., Li, Y., et al. (2019)	China	Residential	Prefabricated components	A1 to A5	38 / 40 (A5)	52	No, N/C
Aye, L., et al. (2012)	Australia	Multi-story residential buildings	Steel prefabricated modules	Entire life cycle	Yes, N/C	51	81
Al-Hussein, M. (2009)	Canada	Multi-story residential buildings	Modular construction, Steel structure	A5	43	Yes, N/C	No, N/C

#### 4.1 Efficiency of Prefabrication in Reducing Carbon Footprint

Comparative analysis between current industrial practices and scientific studies on environmental impact reveals a significant gap in the consideration of CO<sub>2</sub> emissions throughout the life cycle of construction projects. Key life cycle phases, particularly those related to production and construction processes, are critical stages where carbon emissions can be significantly reduced through the integration of prefabrication techniques.

Studies by Al Hussein (2009) and Padilla-Rivera & Blanchet (2017) demonstrate the proven effectiveness of modular prefabrication in reducing CO<sub>2</sub> emissions. By optimizing construction processes and minimizing energy requirements, prefabrication has been shown to be highly effective in lowering the carbon footprint of construction projects.

The illustrations 3 and 4 below highlight how prefabrication impacts the different life cycle phases of construction:

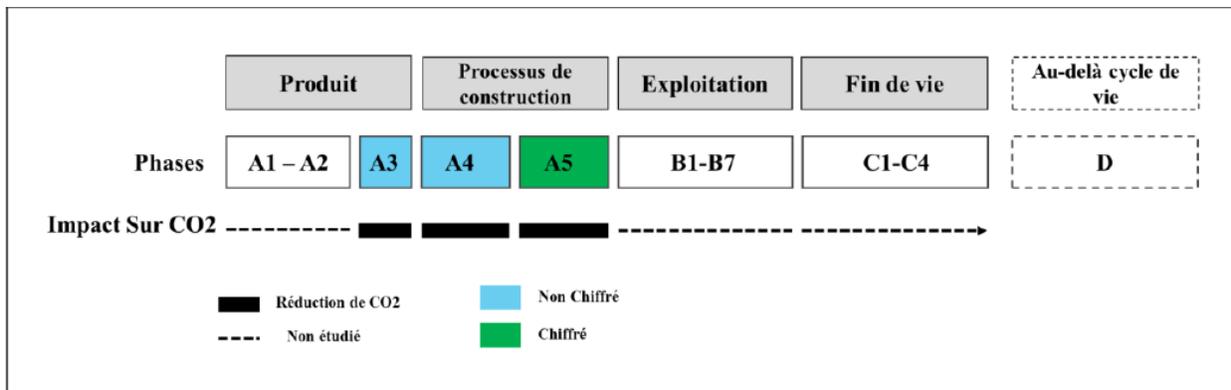


Figure 3 :Key intervention phases of modular prefabrication according to the study by Al-Hussein, M. (2009)

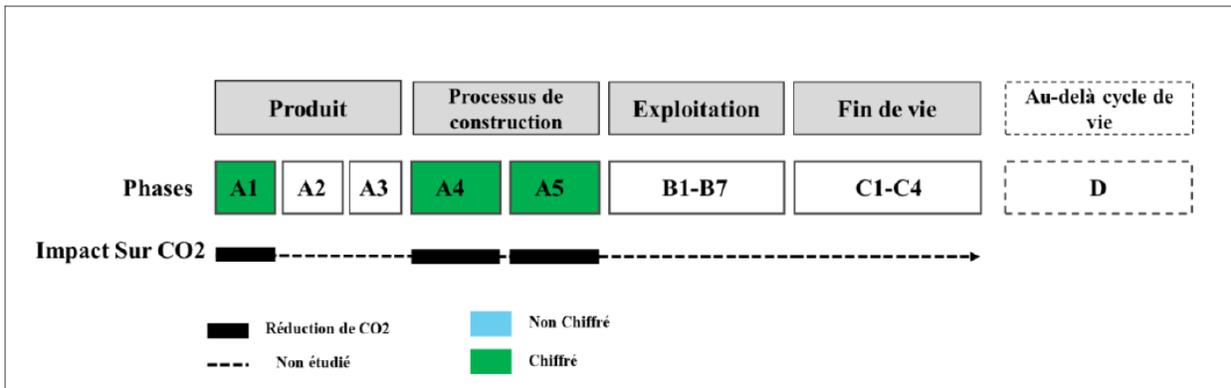


Figure 4:Key phases of prefabrication intervention according to the study by Padilla-Rivera, A., & Blanchet, P. (2017)

## 5. DISCUSSION

This study demonstrates that prefabrication significantly reduces the carbon footprint of multi-story residential buildings, particularly during the production (A1–A3) and construction (A4–A5) phases. It minimizes on-site waste through efficient material use, reduces CO<sub>2</sub> emissions associated with waste management, and enhances quality control, thereby decreasing emissions from construction activities.

The environmental impact of prefabrication varies depending on materials, degree of prefabrication, and transportation distances. Prefabricated wood enables carbon sequestration, while concrete and steel have high carbon footprints due to energy-intensive production. Fully prefabricated modules reduce carbon impact compared to partial prefabrication, primarily due to shorter construction times and reduced on-site movements. Transportation logistics also influence emissions, highlighting the importance of optimizing distances and supply chains.

Compared to traditional methods, prefabrication can reduce carbon emissions by up to 28.8% through optimized material use, waste reduction, and energy-efficient factory production. However, maximizing environmental benefits requires contextual planning, considering design, logistics, and local regulations from the initial design phase.

Digital tools like Gestimat and BIM optimize prefabrication processes and reduce carbon footprints. Gestimat evaluates the environmental impact of materials across life cycle phases, allowing for detailed analysis and informed design decisions. BIM enhances stakeholder coordination, material planning, and logistics, reducing waste and on-site movements. Integrating these digital tools early in the design phase maximizes their environmental benefits.

Despite its environmental and economic advantages, prefabrication adoption faces challenges. High initial costs, logistical complexities, and industry resistance to change limit its widespread implementation. Misconceptions about complexity and underestimation of its benefits hinder acceptance. To overcome these barriers, better communication of prefabrication's economic and environmental advantages is needed, supported by pilot projects and case studies demonstrating its positive impact on carbon footprints.

The evolution of prefabrication practices is influenced by environmental regulations, yet carbon footprint reduction is not a priority for many industry stakeholders. Enhancing training on the environmental and economic benefits of prefabrication, coupled with financial incentives and favorable regulations, could accelerate the shift towards sustainable practices in multi-story residential construction.

## **6. CONCLUSIONS**

Climate change is an increasing global concern, largely exacerbated by GHG emissions. Among the major contributing sectors, the construction industry plays a leading role, accounting for a significant share of global energy consumption and CO<sub>2</sub> emissions. This situation calls for a transformation of current practices to reduce the sector's carbon footprint and address contemporary environmental challenges.

The objective of this research was to evaluate the impact of prefabrication on reducing the carbon footprint in the construction sector, particularly in multi-story residential buildings. The results demonstrate that prefabrication, by optimizing material use and reducing on-site waste, significantly decreases CO<sub>2</sub> emissions, particularly during the production and construction phases. These findings confirm the hypothesis that prefabrication contributes to better resource management and carbon footprint reduction compared to traditional construction methods. In summary, although prefabrication holds great potential for reducing the carbon footprint in multi-story residential construction, its success depends on overcoming industry obstacles and promoting broader adoption of digital technologies.

This study offers some scientific contributions to the field of sustainable construction by providing evidence of the environmental benefits of prefabrication, particularly in reducing carbon emissions during the production and construction phases of multi-storey residential buildings. It also highlights the potential of digital tools such as BIM and LCA to optimize material use and enhance environmental performance. However, the study has some limitations. The sample size for interviews and questionnaires was relatively small, and limited access to industry data restricted the depth of the quantitative analysis. Moreover, the focus on the Quebec context and the exclusion of the full building life cycle—including the use and end-of-life phases—limit the generalizability and comprehensiveness of the findings. These limitations point to promising avenues for future research, including the expansion of prefabrication practices, improving digital tools for more accurate environmental assessments, and addressing current economic and organizational challenges. This will allow the construction sector to move closer to its sustainability goals and significantly

reduce its contribution to climate change. In addition, future studies should focus on assessing the long-term impacts of prefabrication, examining in particular the performance of buildings over their entire lifecycle.

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