

INDUSTRIALIZED CONSTRUCTION INDEX (ICI): A PROJECT INDICATOR FOR INDUSTRIALIZATION ASSESSMENT

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ABSTRACT

Industrialized Construction represents a fundamental paradigm shift toward a product-based approach to address chronic productivity and quality issues in the sector. However, the lack of a standardized, scientifically rigorous metric to quantify industrialization maturity hinders strategic goal-setting and cross-project benchmarking. This paper presents and validates the Industrialized Construction Index (ICI), a quantitative framework measuring maturity across five pillars: Standardization, Prefabrication, Modularization, Automation, and Digitalization. Utilizing a multi-case study approach, the ICI was deployed across 61 residential projects in Colombia and 33 projects in France. Findings demonstrate the indicator's sensitivity to diverse market realities, revealing a 33% industrialization maturity in the Colombian market-driven primarily by design standardization, while French projects exhibited higher variability through advanced off-site solutions like volumetric modules and timber-frame facades. The research confirms the ICI as a robust, cross-border assessment tool that allows construction companies to move beyond subjective classifications toward verifiable metrics, facilitating the correlation between industrialization levels and global project performance.

KEYWORDS

Industrialization, prefabrication, standardization, modularity, automation, digitalization.

INTRODUCTION

Industrialized construction (IC) is a concept that integrates a range of industrial manufacturing techniques to improve traditional building methods (Marks, 2020). Other authors, such as (Qi et al., 2021), define IC as the adaptation of traditional construction to an industrialization framework through the integration of manufacturing concepts and tools.

Other authors like goes further explaining that IC implies a paradigm shift in the industry heavily influenced by the principles of Lean manufacturing. It is fundamentally based on modern production strategies and a process-oriented thinking including: the continuous development of processes, the relocation of processes to a controlled environment, the standardization of systems and designs, the use of a pull production system, the utilization of optimization tools, information technologies, and smart manufacturing, and the elimination of defects, waste, and inventories, among others (Lessing et al., 2005).

Malmgren (2014) argues that IC and “industrialized housing production is somewhere between manual production and mass production” (p. 31). Essentially, the long-term ideal of IC is to produce houses in the same way cars are produced (Li et al., 2020), while the antithesis

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remains the manual design and construction of every single element of a building. Consequently, IC processes evidently stem from lessons learned in the manufacturing industry, as IC utilizes a product-based approach, contrary to the project-based approach found in the construction industry (Kedir & Hall, 2021). For this critical transition to occur, it is essential to develop and validate indicators that allow construction companies to accurately position their projects on this path towards industrialization and formulate strategic goals around verifiable metrics.

(IC) emerges as a major trend to solve several of the persistent problems of decreasing productivity and low quality that plague the construction industry. These challenges are intrinsically related to the manual, intensive, repetitive, and often artisanal nature of work that has historically dominated the sector (Closs & Kadani, 2020). Consequently, construction projects frequently suffer from high-cost overruns, scheduling delays, excessive waste generation, and high levels of risk. To counter these issues, Pullen et al. (2019) define the principal objectives for IC, which include: Increasing labor productivity and efficiency, reducing overall project costs, replacing manual labor with mechanized work, simplifying on-site tasks, improving overall quality of projects, reducing the environmental impact, enabling faster project traceability, and accelerating the planning and customization of new projects.

Each of these objectives can be measured using Key Performance Indicators (KPIs) currently utilized in construction project management to analyze global sustainability of the project. However, to accurately determine the impact that IC has on these outcomes, it is first essential to define a scientifically rigorous methodology to quantify industrialization maturity itself. This would allow us to study correlations between a project's level of IC and its performance KPIs. For instance: To serve as an effective assessment tool, the methodology must be conceptually based, scientifically consistent, and systematically calculable, using data readily available from construction projects.

STATE-OF-THE-ART

To date, no standardized indicator currently measures IC in either France or Colombia. While various studies propose scores or degrees using different methodological approaches, a comprehensive and globally validated framework remains elusive. Therefore, the following section provides a chronological review of these existing methods to evaluate their scope and assess their suitability for systematic project assessment:

Industrialized housing: Definition and categorization (Lessing et al., 2005): This theoretical framework, proposed by J. Lessing, L. Stehn, and A. Ekholm (2005), constitutes one of the earliest comprehensive studies aiming to define and evaluate IC within the Swedish housing sector. The authors identified fundamental concepts: planning and process control, developed technical systems, off-site manufacturing, long-term participant relations, integrated supply chain management, customer focus, information and communications usage, and systematic performance measurement. Then, they established an evaluation model designed to characterize the level of achievement of each of these eight interdependent concepts on a scale from 0 to 4.

Constructability Appraisal System (CAS): Mandatory in Singapore since 2005, “constructability” provisions indirectly measure IC through the B-score. This indicator incorporates concepts like efficiency and standardization, quantifying a project's constructability based on variables such as floor areas and wall lengths, with additional points for DfMA practices. However, industrialization and constructability are distinct, as the latter refers to the design's inherent ease and efficiency of execution. (Attouri et al., 2022).

Pre-Manufactured Value (PMV): The United Kingdom government has led the deployment of industrialized construction strategies, to address national housing shortages and sector decarbonization. In 2016, Mark Farmer's review introduced a 7-category Modern Methods of Construction (MMC) framework, featuring the Pre-Manufactured Value (PMV) as a key metric to quantify manufactured components relative to total project cost. Furthermore, the Affordable

Housing Programme (2021-2026) now requires at least 25% of financed homes to utilize MMC, formalizing the commitment to modernization (Farmer, 2019). This indicator represents the first quantitative approach to measure IC level based on project data. Nevertheless, its focus is constrained to prefabrication, the factory production of components for site assembly. As stated by Andersson & Lessing (2017), IC is not limited to prefabrication, but rather includes all systematic, controlled, and standardized production of construction systems, regardless of whether the components are produced off-site or in-situ. This implies that IC encompasses the entire delivery process and a holistic life cycle vision (Goh & Loosemore, 2017), so the indicators must reflect this comprehensive scope.

Modular construction: From projects to products (Bertram et al., 2019): Similarly, various studies categorize prefabricated construction, notably McKinsey & Company's report on the industry. These classifications typically depend on module dimensionality (1D, 2D, 3D), structural character, or component complexity. Even though this classification is useful for classification in typologies, this approach lacks a quantitative index of prefabrication.

Off-site Rate (THS for Taux Hors-Site): In France, environmental regulations significantly drive technological shifts. The Réglementation Environnementale 2020 (RE2020) mandates life cycle carbon reductions for materials and equipment. To support this, the Association Filière Hors-Site France (AFHSF) developed the Off-site Rate (THS) in 2023, allowing project owners (MOA) to assess off-site construction against RE2020 thresholds. Inspired by the UK's PMV, THS measures the proportion of superstructure costs dedicated to off-site construction, excluding earthwork, landscaping, and networks (Attouri et al., 2022). Implementing the THS revealed a critical limitation: it highly depends on the referential framework used for its calculation. Results vary significantly based on whether components are classified as off-site manufactured, creating a conceptual debate concerning elements like windows, carpentry, or even pre-cast double walls. While these elements have existed since the post-war era, their traditional application often lacks improvements of modern IC principles. This dependency on subjective classification demonstrates that a metric focused solely on the cost ratio of off-site elements requires a multidimensional approach, as suggested by the UK's MMC methodology.

Industrialized Construction Index (ICI): Originally proposed as the NIC in the thesis "*Cálculo del nivel de industrialización en la construcción*" (Sanchez Ruiz, 2021), it provides a quantitative method to assess IC maturity in building projects. The ICI establishes a conceptual framework built upon five distinct axes of industrialization. Then, it proposes a methodology to apply specific formulas to calculate a partial index (0–100%) for each pillar for every component of the construction project. The final aggregated ICI is then weighted according to the component's importance, typically based on its cost proportion or its influence on the project schedule, aligning the metric with the strategic goals of the construction company.

This article presents and validates the Industrialized Construction Index (ICI). Adopting a descriptive approach, it details the results of the ICI method as applied to a leader in the Colombian housing construction industry (2022); there, the index was deployed across 60 residential projects, tracking year-to-year evolution and serving as a corporate KPI. Similarly, the method was applied to 30 projects of a major building company in France, where it complemented the Off-site Rate (THS) indicator from the AFHSF and facilitated a cross-performance analysis of the impact of IC on CO₂ emissions and direct costs. Finally, the article analyses these results to offer conclusions on the observed patterns of industrialization methods and maturity within these two distinct national construction contexts.

METHODOLOGY

The primary objective of this study is to validate the ICI methodology developed by Sanchez Ruiz (2021) through testing on diverse projects. It is structured to assess the indicator's sensitivity, reliability, and cross-border applicability through multi-case study analysis.

FRAMEWORK SELECTION AND THEORETICAL BASIS

Followed by IHC framework, key factors around IC have evolved into five distinct pillars that construct the modern definition: Standardization (S), Prefabrication (P), Modularization (M), Automation (A), and Digitalization (D) (Wang et al., 2018). To clarify the role of each pillar, Sanchez Ruiz (2021) employs the graphic analogy of a house, inspired by Jasat (2019) and Marks (2020). Then, he proposes formulas for calculating their respective indices (0–100%) relying on measurable or estimable variables, such as production rates or the cost of components.

Standardization

Standardization is understood as the "extensive use of components, methods, or processes in which there is repetition, regularity, and antecedents of correct practices" (Li et al., 2019, p. 2). It can be broadly differentiated into two categories: design and process. Standardization of design consists of using standardized designs for building components or complete modules that are applied repetitively throughout a project, which translates into fewer measurement errors and less material wastage (Ottinger et al., 2020). On the other hand, standardization of process focuses on the repetition of activities using the same sequence, methodology, and resources, regardless of the design being applied (Kedir & Hall, 2021). It enables learning curves to be established, thereby increasing the efficiency and quality of execution and facilitating the integration of automation tools.

An important concept utilized within the framework of standardization in IC is Design for Manufacture and Assembly (DfMA), which integrates the concepts of both design standardization and process standardization, all while being underpinned by Lean manufacturing principles. To explain DfMA within the context of the construction industry, the analogy of Lego bricks is often used: Design for Manufacture (DfM) or Sd corresponds to the design of each individual brick, complete with its specifications and tolerances. Design for Assembly (DfA) or Sp corresponds to the design of the instructions for assembling a specific structure using those standardized Lego bricks (Marks, 2020).

The formulas proposed to calculate the indices are as follows:

- E_D : Design standardization index
- E_P : Process standardization index
- N_D : Number of different designs per component
- N_P : Number of different processes per component
- N_C : Number of building components

Effective application of this formula requires the prior division of the building into distinct activities. An activity is defined by a measurable, comparable unit and a constant cost base (e.g., m² of reinforced concrete, wood or metal frame walls are distinct. For each one, the number of components considered by standards is counted based on a set of objective criteria. Then, it is weighted by the activity's direct cost proportion to calculate the index for the entire project.

Prefabrication

Prefabrication, also known as Off-Site Construction (OSC), refers to the production of building components within an specialized factory or controlled environment, followed by their transportation to the construction site for assembly or installation (Qi et al., 2021). For instance, prefabrication is directly related to the quantity of work executed in the factory versus on-site.

The method initially proposed a prefabrication index based on labor time, incorporating off-site fabrication, transport, and on-site assembly durations (Sanchez Ruiz, 2021). However, during application a major limitation was encountered: a General Contractor does not always have access to precise off-site fabrication time data from their subcontractors "prefabricators",

hindering the project-based calculation. As consequence, the formula evolved to a project position spectrum in between a full off-site scenario (100%) and full traditional scenario (0%):

- P : Prefabrication index
- t_{IS} : Traditional or on-site construction time (old scenario)
- t_R : Real construction time (actual scenario)
- t_{OS} : Off-site construction time (goal scenario due to prefabrication)

The t_R is measured directly on-site or can be extracted from a construction schedule. For its part, the t_{OS} , which supposes that construction is entirely industrialized, can be drawn from state-of-the-art research. In the formula, it is assumed that it is practically "impossible" to execute the activity in a shorter time using currently known construction methods. Therefore, this time must be highly optimistic, accounting for minimal possible time losses and near-ideal conditions. Conversely, t_{IS} must assume that the construction is realized entirely on-site, without any prefabrication methods. This time is recommended to be based on the durations from a prior, similar construction project or historical records within the company, while being deliberately pessimistic. To obtain an objective level of prefabrication, it is important to consider t_{IS} as the baseline against which all gains from prefabrication are measured.

Modularity

Modularity refers to the process of designing, manufacturing, transporting, and installing building "modules" under controlled conditions (Qi et al., 2021). It can be considered the highest level of prefabrication, but the key difference lies in the unit of focus: Modularization concentrates on the prefabrication of modules, which are defined as building units formed by the off-site assembly of multiple elements from different systems, constituting a functional part of the building itself (Kedir & Hall, 2021).

As the P index does not consider this inherent multisystemic characteristic, this formula is proposed using the same division as the E index. Then, it is weighed by the activity's direct cost proportion to calculate the final for the entire project.

- M : Modularity index
- N_M : Number of modules
- N_C : Number of building components
- c_i : Direct cost of each component
- C_D : Total direct cost

For this research, the criteria suggested is to classify an element as modular is the requirement that the element must include multiple systems of the building, such as structural, insulation, architectural, hydraulic, or electrical components. Based on this multisystemic criteria, for example, a steel-framed façade is not considered modular (even if it is prefabricated) unless it contains integrated exterior joinery and insulation, or cladding, which would then affirm it as a 2D module. It is reiterated that in this study, the modular criterion has no dependence on dimensionality (2D panel or a 3D volumetric unit).

Automation and mechanization

Automation involves using autonomous machinery or robots to replace manual labor in monotonous tasks (Marks, 2020), distinct from mechanization where human operation is required. While essential for modern construction, standard mechanization, such as the use of backhoes, trucks, or tower cranes, is considered a foundational baseline rather than an innovative feature of modern IC.

As for the P index, a time-based formula is proposed:

- A : Automation index
- t_A : Automatic production time
- t_M : Machine production time
- t_O : Hand-work production time
- r : Production rate (m³/hH, m²/dH, ud/dH...)
- U : Production units (m³, m², ud...)

Digitalization

Digitalization in construction is primarily driven by Building Information Modeling (BIM), offering immense potential to enhance industrialization (Li et al., 2020). However, the Level of Detail (LOD) in BIM typically reflects design digitalization rather than the construction process itself. To bridge this gap, modern technologies, including sensors, Digital Twins (DT), Internet of Things (IoT), Machine Learning (ML) and Big Data, must be actively integrated into execution. Effectively implementing these requires an interactive, proactive, and method-based BIM approach that moves beyond static modelling to support construction process.

As a result, the formulas proposed to calculate the design and process digitalization are:

- D_D : Design digitalization index
- D_P : Process digitalization index
- c_t : Score from 0 to 5 from the technologies assessment matrix (Sanchez Ruiz, 2021)

Finally, the calculation of the Industrialized Construction Index (ICI) consists on the ponderation of each index by some constants decided by the construction company's experts:

CASE STUDY SELECTION: A CROSS-REGIONAL APPROACH

To ensure the indicator remains robust across varying socio-economic and technical landscapes, four construction projects were selected using a *purposive sampling strategy*. The selection represents two distinct construction ecosystems:

Group A (Colombia): 61 projects selected to represent a market characterized by emerging IC and a high reliance on manual labor, largely as a response to the urgent demand for social housing (VIS as *Vivienda de Interés Social*) to address the national housing deficit. Typical VIS projects consist of five-story walk-up buildings with four apartments per floor, predominantly utilizing structural masonry or reinforced concrete, delivered in a "bare-shell" state, providing only essential amenities (toilet and sink). A second common VIS typology involves high-rise buildings (exceeding eight stories) constructed with reinforced concrete cast in reusable metallic formwork. This method is locally referred to as "industrialized" because the formwork panels are systematically cycled from floor to floor without full disassembly. Non-VIS projects utilize similar high-rise methods but include comprehensive on-site interior finishes and higher-specification installations. For the purpose of this study, single-family housing and tertiary buildings (such as schools and shopping malls) were calculated but excluded from the comparative analysis with France to ensure typological consistency.

Group B (France): 33 projects selected to represent a mature market governed by strict environmental regulations (RE2020), high labor costs, and advanced adoption of 2D/3D pre-assemblies. The selected projects reflect a diverse range of structural systems, including reinforced concrete, pre-cast concrete, and structural timber frames. In this context, prefabrication is more advanced, incorporating solutions such as timber-frame facades (FOB) with integrated external joinery and/or insulation. Other common industrial applications in this group include volumetric modular bathrooms and prefabricated technical shafts.

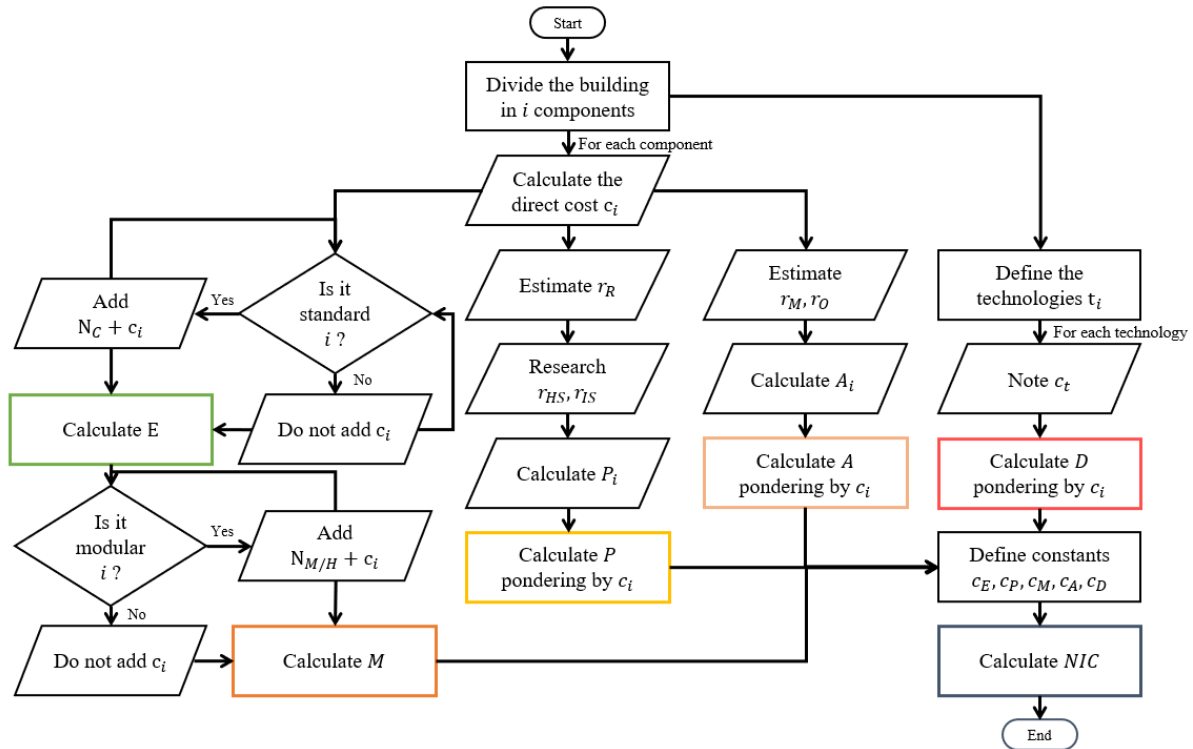


Figure 1: ICI calculation method systemic representation.

DATA ACQUISITION AND TECHNICAL VERIFICATION

Data collection was executed through a triangulation method to ensure the accuracy of the indicator's inputs and validate sources of information for each one of the variables:

- **On-site observations:** Verification of production rates and workforce analyses: t_R
- **Technical documentation:** Different project technical documentation was consulted to calculate the following variables: Work Breakdown Structure budget distribution (WBS): c_i, c_D ; BIM execution plans: N_C, N_D, N_P, N_M ; company's historical Bills of Quantities (BoQ): t_{IS}, t_M, t_O
- **State-of-the-art research:** Drawn from existing literature or reports from other construction firms with a high level of IC development: t_{OS}
- **Expert interviews:** Semi-structured interviews with Project Managers in both countries to validate the "soft" parameters of the indicator, such as: LOD, c_t

EVALUATION PROTOCOL

The testing of the indicator was conducted in three steps:

- **Input mapping:** Import and mapping the raw project data from Colombia and France to the universal parameters defined in the original indicator framework.
- **Scoring & computation:** Applying the weighted formulas to generate a final ICI for each project using the systemic process illustrated in Figure 1.
- **Comparative sensitivity analysis:** Assessing whether the indicator correctly identified the industrialization gap between the two regions or if local variables (e.g., specific Colombian seismic requirements or French thermal regulations) skewed the results.

RESULTS

Group 1 (Colombia): Following the established procedure, the Standardization (E), Prefabrication (P), Automation (A with the definition of mechanization), and Digitalization (D)

indices were calculated for 61 construction projects in Colombia. The statistical distribution of results of 55 housing projects is presented in Figure 2.

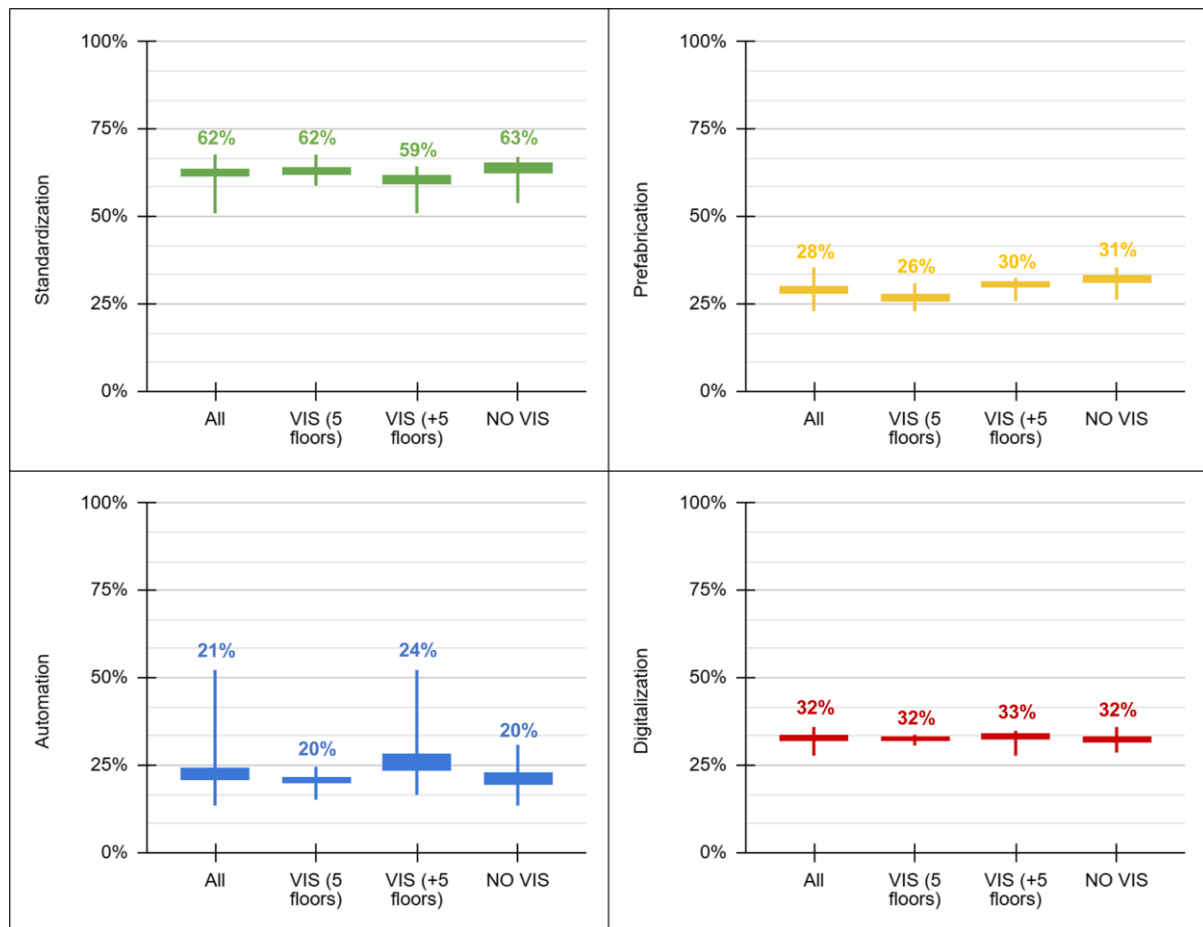


Figure 2: E, P, A & D indices result for Colombian projects.

In coordination with the company's management, the weighting coefficients for the final ICI calculation were defined as follows, reflecting the strategic profile of a traditional firm in the early stages of IC. Modularization was assigned to null weight as the current methods lack multisystemic prefabricated elements, making a modular referential inapplicable. Conversely, prefabrication was prioritized as the primary strategic lever for productivity, while digitalization had secondary role in the current operational focus over automation.

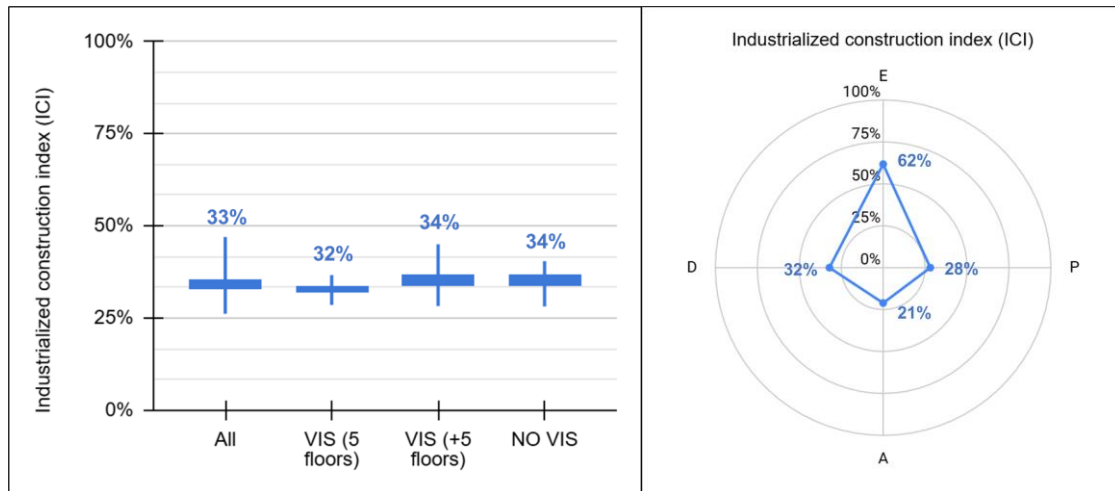


Figure 3: Global ICI result for Colombian company.

In general, the results demonstrate high consistency across all indices, as evidenced by the low variance between projects utilizing similar construction methodologies. The highest variation occurred within the automation (A), specifically in high-rise projects (exceeding five floors). This variance is attributed to the extensive mechanized excavation required for these structures, where a larger proportion of the budget is allocated to high-mechanization activities.

These findings confirm that the Colombian market has primarily developed its IC through standardization. This was an expected outcome, as both VIS and even non-VIS projects frequently deliver over 300 highly repetitive units with similar layouts and basic functional requirements. In non-VIS projects, specialized interior finishes, such as wood furniture, doors, and flooring had a slight repercussion on the prefabrication index, as a larger share of the budget is dedicated to these activities, which currently offer a narrow margin for prefabrication improvement. Ultimately, the development of IC in the region remains at a premature stage, accurately reflected by a global ICI of 33%, indicating that the evaluated projects have completed approximately one-third of the transition towards a fully IC model.

Group 2 (France): Similarly, the Prefabrication (P) and Modularization (M) indices were calculated for 24 projects in France, 18 of which were residential. This selection by IC team's management was driven by data availability, prioritizing variables that could be reliably extracted from corporate records, bills of quantities, and budgetary documents. Consequently, in this preliminary phase, Standardization (S) and Digitalization (D) were omitted, and Automation (A) was excluded due to conceptual ambiguities regarding its definition and the logistical challenges of conducting consistent on-site observations across all project sites.

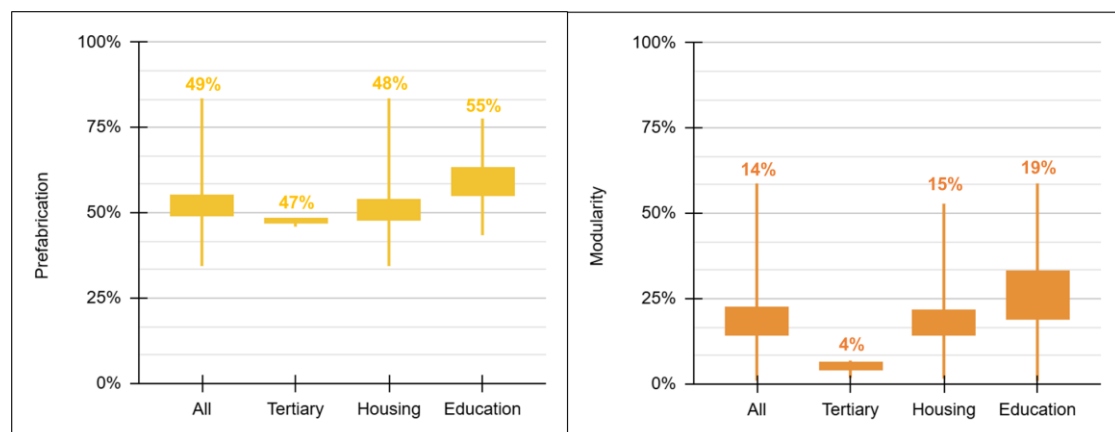


Figure 4: P & M indices results for French projects.

Shown in Figure 4, results exhibited significantly higher variability as anticipated, because the sample encompasses a heterogeneous range of construction methods. Through sensitivity analysis, we evaluated the individual impact of various technical solutions on both the indices. This analysis allows for a granular understanding of methods choices, such as the adoption of 2D panels versus 3D volumetric modules, influence the project's ICI, summarized in Table 1.

Table 1: ICI variable sensitivity analysis for different construction methods (France).

ICI variation per project	P (%)	M (%)
Precast concrete walls	2pp	0pp
Precast concrete insulated walls	8pp	8pp
Timber façade frames (FOB)	3pp	0pp
Insulated and windows integrated FOB	12pp	12pp
Volumetric modular bathrooms	7pp	7pp
Prefabricated technical shafts	8pp	8pp
3D modular structure	50pp	50pp

CONCLUSION

This research objectively characterizes the implementation of Industrialized Construction (IC) through the Industrialized Construction Index (ICI). By decomposing the broad concept of IC into five measurable pillars, this study provides a feasible framework applicable across diverse international contexts. The ICI allows the systemic application across diverse construction methods, as an empirical tool for direct on-site observation, following a "measure-and-calculate" approach. Furthermore, the ICI calculation exercise allowed to formalize broader project KPIs, including productivity, quality, and environmental impact. Future research should focus on correlating individual ICI pillars with these metrics to quantify the specific impact of IC on project performance, as the major goal of IC is to address these systemic industry challenges.

However, the robustness of the global methodology relies heavily on the consistency of the underlying assumptions, application criteria, and data sources. Indices may fluctuate based on the level of granularity used to decompose the building structure and the specific information sources consulted. In particular, the M index arithmetically analogous to the formulas used to calculate the PMV in the United Kingdom and the THS in France. Consequently, a primary limitation of the formula is that results are sensitive to the selected framework referential and the definition of "modular" elements, which remains contingent upon the reference criteria employed. In this study, although the specific referentials for Colombia and France differed to reflect local market realities, the core conceptual recommendations of the ICI method were strictly maintained.

To conclude, while the Colombian market exhibits an immature level of IC despite high standardization to address the housing deficit, the French market shows greater advancement in prefabrication. In France, primary challenge lies in integrating multi-system components into off-site elements, as suggested by the modular approach. Such integration would not only improve modularity levels but also maximize the benefits of IC methods. However, since the French definition focuses heavily on off-site construction, it often neglects standardization, automation, and digitalization, pillars that remain essential for a comprehensive evaluation and future cross-market comparisons.

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