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METHOD OF INDUSTRIALIZATION POTENTIAL ANALYSIS OF CONSTRUCTION SYSTEMS

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ABSTRACT

Construction is a production system characterized by inefficiencies associated with its processes. Industrialized construction (IC) is a promising approach as an optimization mechanism based on decreased variability. In this regard, it stimulates the standardization of work, which is an essential lean management principle to improve the production system. However, IC presents an incipient level of adoption and implementation. This paper describes a method for the industrialization potential analysis of construction systems (IPA), allowing design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance. It was developed through an action-oriented framework based on the action research methodology. Researchers, construction companies, and the cohesive entity of the construction sector (Industrialized Construction Council, ICC) participated.

KEYWORDS

Industrialized construction, standardization, modular coordination, preassembly.

INTRODUCTION

The construction industry has low productivity rates, with 40% less real gross value added per hour worked than the manufacturing industry (McKinsey & Company, 2017). This low performance has been associated with craft production logic, low specialization, precarious working conditions, and high impact of labor (Escrig Pérez, 2010).

Industrialized construction (IC) is a production process characterized as systematic, controlled, and standardized, oriented to constructing well-defined systems (Lessing, 2015). IC has been associated with greater efficiency, related variability reduction (Wangwe et al., 2014), continuity of material and information flows (Vrijhoef, 2016), constructability, and control over work environments (Jaillon & Poon, 2009). However, IC presents an incipient level of adoption and implementation (Lundberg et al., 2019).

A paucity of studies specifically address methodologies oriented to the systemic application of industrialization strategies from the early stages (Mohamad et al., 2014). Because of the above, the decision to use these is often not made early enough in the

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construction design process, and conventional designs have to be adapted later (Aldridge et al., 2001). Furthermore, these decisions are not based on rigorous data but on anecdotal evidence (Pasquire & Gibb, 2002).

The paper presents a theoretical model developed to allow design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance as support for decision-making associated with industrialization efforts.

CONCEPTUAL APPROACH

STANDARDIZATION

Standardization (ST) has been a concept used in the construction industry at different scales: standards of materials and processes, particular specifications of a client related to standard items or processes, standard products or produced with standard components and processes, and use of standard components or procedures in a particular project (Gibb, 1999). For the purposes of this research, it was taken to be the extensive use of components, methods, or processes in which there are regularity, repetition, and background of successful practice and predictability (Gibb, 2001).

MODULAR COORDINATION

Modular Coordination (MC) is a measurement standard for elements of construction systems (Yunus et al., 2016) to coordinate the dimensions and spaces of the building and its components as multiples of a basic unit or basic module. The implementation of the MC concept in component design can improve the total constructability of the construction project (Zainol et al., 2013). Likewise, MC contributes to optimizing materials and elements by eliminating waste in terms of variability options and margins of error of the products and enabling them to be assembled without cuts or with the least of them (Banihashemi et al., 2018).

PREASSEMBLY

Preassembly (PA) has been related to changing the industry's mentality (Aapaoja & Haapasalo, 2014). It refers to how different materials and components are joined in another place from the subsequent install following (Qi et al., 2021). So a substantial part of the work part of the final assembly work is completed before installation in its final position (Pasquire & Gibb, 2002). It transforms the fragmented linear construction of buildings based on the installation site into integrated manufacturing and assembly of value-added factory-made building components (Wuni et al., 2020). It is related to benefits in time, cost, and quality, associated with economies of scale, increased productivity (Xue et al., 2018), greater workflow continuity, reduced number of contractors on site, and shorter construction time (Hwang et al., 2018).

RESEARCH METHOD

The proposed model was developed through an action-oriented framework based on the action research methodology. This actively drives change in real contexts through action (Davison et al., 2004). The framework consists of cycles of action and reflection, carried out in a collaborative workgroup comprised of representatives from the Research Group, the cohesive entity of the construction sector (Industrialized Construction Council), and representatives of construction companies. The framework has four phases: Pre-Action phase, Action planning phase, Action implementation phase, and Learning phase. These and their associated activities are presented in Figure 1.

The Pre-Action phase seeks to build a knowledge base and identify the challenges and the specific need. In the diagnosis is desired to identify the problem that the action will address and understand the current context (Staron, 2020). The referencing consists of a literature review in scientific databases and a review of the state of practice in the local context, oriented to decision support methods associated with selecting processes to industrialize. In the Action planning phase, the collaborative working group established the objectives of the action, its scope, terms of the industrialization concepts to be integrated, and the way to evaluate the goals. In the Action implementing phase, the specific action is carried out: developing a theoretical model to allow design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance. The learning phase is a moment of reflection on the previous action research cycle. Following the cyclical process model, a decision is made on whether additional cycles are needed (Davison et al., 2004), and future implementation actions are defined.

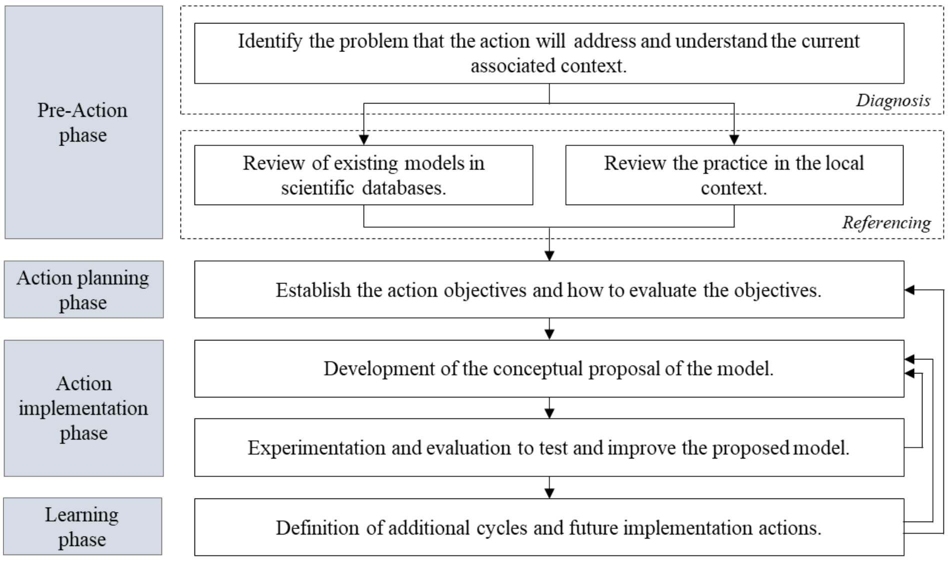

Figure 1. Action-oriented framework

INDUSTRIALIZATION POTENTIAL ANALYSIS METHOD (IPA)

INTEGRATED INDUSTRIALIZATION STRATEGIES

The theoretical model developed integrated the following industrialization strategies:

- *Standardization (ST):* Project standardization was integrated into the developed model from the scope of standardization of components typologies.
- *Modular coordination (MC):* It was integrated based on the basic module, known as M, which is equal to 100 mm (Noor et al., 2018) and can be defined in n*M, resulting in several modules.
- *Preassembly (PA):* Preassembly was integrated based on the degree of integration proposed by (Gibb, 1999): *(i)* component manufacturing and sub-assembly, where components that integrate various materials are manufactured and assembled in one place, *(ii)* Nonvolumetric preassembly, where the preassembled units do not create a usable space, *(iii)* Volumetric preassembly, where the assembled elements

enclose usable space, and *(iv)* Modular Building, where the volumetric units, in addition to enclosing the useful space, themselves form the building.

POTENTIAL ANALYSIS PROPOSED

IPA is based on two temporary approaches: past experiences and present conditions, and six lines of approach: previous implementations, project performance, relevance characteristics, implementation feasibility, factors, and contribution measures. These and their associated analysis elements are presented in Figure 2.

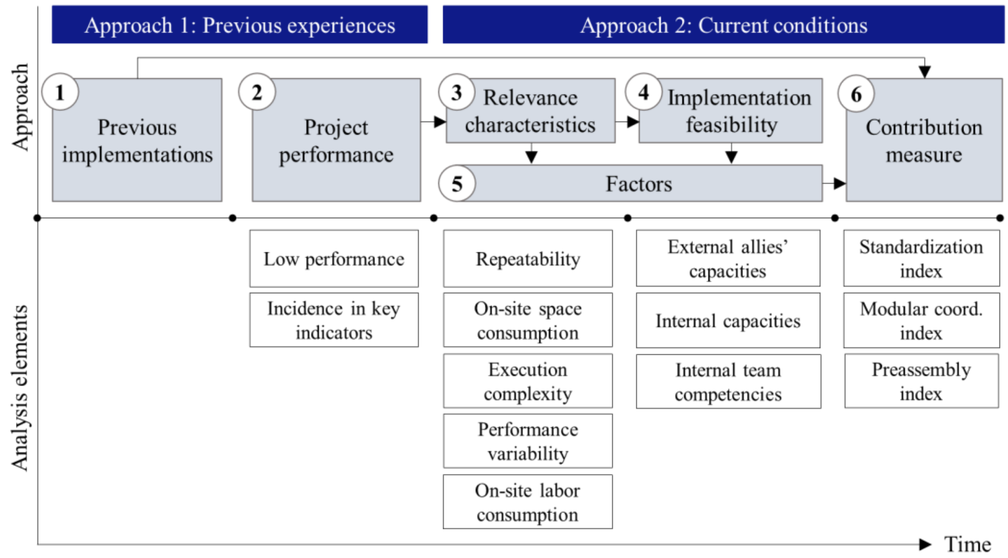

Figure 2. Potential analysis proposed

PREVIOUS EXPERIENCES

Step 1: Previous implementations

Construction systems are selected based on reviewing previous implementations, both successful and those with identified elements to improve. These systems are related to specific industrialization strategies implementations, are pre-selected, and directly go to step 6: contribution measure.

Step 2: Projects performance

Construction systems are selected based on performance analyses of previous similar projects. The analysis must be oriented toward the identification of *(i)* construction systems with the most significant incidence in indicators of interest specific to the current project; and *(ii)* low-performance construction systems in previous projects. Since these systems are selected for their weaknesses but are not linked to implementing a specific industrialization strategy, they must go to steps 3 and 4 to analyze those in the function of the type of intervention.

CURRENT CONDITIONS

Step 3: Relevance characteristics

Pre-selected systems from step 2 are analyzed based on the potential associated with the following characteristics:

- **Repeatability (R)**: Number of times a specific process must be carried out.

- **On-site space consumption (SC):** Total on-site space required for execution or installation, storage, and transportation of elements/materials related to the system.
- **Execution complexity (EC):** It is defined in two terms: Variety, which is related to the diversity of components or variants of the system (Tommelein, 2006), and Connectivity, which corresponds to interdependence with other project systems (Weber, 2005)
- **Performance variability (PV)**: Disparity of results associated with key performance indicators of the different executions of the system.
- **On-site labor consumption (LC):** It is defined in two terms: labor intensity, which refers to the total person-hours associated with carrying out the execution, and density in front of work, which refers to the number of workers concentrated simultaneously in front of work (person/m^2).

The project team must evaluate each of the relevance characteristics. According to the evaluation scale, the score is the value between 0 and 1, assigned to Affectation Elements. The Relevance Characteristic Factor is the average of scores from respective Affectation Elements (Figure 3).

	Affectation elements	Score: 0	0.25	0.50	0.75	1	Relevance Characteristics Factors
R	Repetitions (R_1)	$R<5$	$5\leq R<10$	$10\leq R<20$	$20\leq R<30$	$R\geq 30$	$\mathbf{R}f = \text{Score}(R_1)$
SC	Space consumption (SC_1)	Very low	Low	Average	High	Very high	$\mathbf{SC}f = \text{Score}(SC_1)$
EC	Variety (EC_1)	Very low	Low	Average	High	Very high	$\mathbf{EC}f = \frac{1}{2} * \sum_{i=1}^{2} Score\ (EC_i)$
	Connectivity (EC_2)	Very low	Low	Average	High	Very high	
PV	Cost variability (PV_1)	Very low	Low	Average	High	Very high	$\mathbf{PV}f = \frac{1}{3} * \sum_{i=1}^{3} Score\ (PV_i)$
	Time variability (PV_2)	Very low	Low	Average	High	Very high	
	Quality variability (PV_3)	Very low	Low	Average	High	Very high	
LC	Intensity (LC_1)	Very low	Low	Average	High	Very high	$\mathbf{LC}f = \frac{1}{2} * \sum_{i=1}^{2} Score\ (LC_i)$
	Density (LC_2)	Very low	Low	Average	High	Very high	

Evaluation scale

Figure 3. Relevance characteristics factors

Step 4: Implementation feasibility

Pre-selected systems from step 2 are analyzed based on the feasibility of implementing industrialization strategies, integrating the analysis of:

- **External allies' capacities (EA):** External support, in the local context, is necessary for the implementation in terms of the offer of existing solutions, supplier production capacity, and availability of transportation methods.
- **Internal capacities (IC):** Internal support needed for implementation in terms of production capacity, financing capacity, and on-site space availability for execution or installation, storage, internal transportation, and lifting.
- **Internal team competencies (TC):** Internal support for implementation in terms of project team competencies and a skilled workforce.

The project team must evaluate each of the feasibility elements. According to the evaluation scale, the score is the value between 0 and 1, assigned to Affectation Elements.

The Feasibility Elements Factor is the average of scores from respective Affectation Elements (Figure 4).

	Affectation elements	Score: 0	0.25	0.50	0.75	1	Feasibility Elements Factors
EA	Existing solutions (EA_1)	Very low	Low	Average	High	Very high	$EAf = \frac{1}{3} * \sum_{i=1}^{3} Score\ (EA_i)$
	Supplier capacity (EA_2)	Very low	Low	Average	High	Very high	
	Transp. availability (EA_3)	Very low	Low	Average	High	Very high	
IC	Production capacity (IC_2)	Very low	Low	Average	High	Very high	$ICf = \frac{1}{3} * \sum_{i=1}^{3} Score\ (IC_i)$
	Financing capacity (IC_2)	Very low	Low	Average	High	Very high	
	Space availability (IC_3)	Very low	Low	Average	High	Very high	
TC	Team competences (TC_1)	Very low	Low	Average	High	Very high	$TCf = \frac{1}{2} * \sum_{i=1}^{2} Score\ (TC_i)$
	Skilled workforce (TC_2)	Very low	Low	Average	High	Very high	

Evaluation scale

Figure 4. Feasibility elements factors

Step 5: Factors of Standardization, Modular coordination, and Preassembly

The potential associated with the relevance characteristics and implementation feasibility emerge based on their relationship with integrated industrialization strategies; that is, the type of implementation in which each characteristic acquires more significant importance.

The collaborative workgroup established the relationship between relevance characteristics and the analysis elements linked to the implementation feasibility. According to this relationship, the factors of each industrialization strategy, that is, the Standardization factor (*STf*), Modular coordination factors (*MDf*), and Preassembly factor (*PAf*), are calculated as the media of the factors of the characteristics/elements with which is related, as presented in Table 1.

Table 1. Factors of Standardization, Modular coordination, and Preassembly

Characteristics/ Elements	Standardization	Modular Coord.	Preassembly
Repeatability	$ST_1=Rf$	$MD_1=Rf$	$PA_1=Rf$
On-site space consumption			$PA_2=SCf$
Execution complexity	$ST_2=ECf$	$MD_2=ECf$	$PA_3=ECf$
Performance variability	$ST_3=PVf$		$PA_4=PVf$
On-site labor consumption			$PA_5=LCf$
External allies' capacities			$PA_6=EAf$
Internal capacities	$ST_4=ICf$	$MD_3=ICf$	$PA_7=ICf$
Internal team competencies	$ST_5=TCf$	$MD_4=TCf$	$PA_8=TCf$
	$STf = \frac{\sum_1^5 (ST_i)}{5}$	$MDf = \frac{\sum_1^4 (MD_i)}{4}$	$PAf = \frac{\sum_1^8 (PA_i)}{8}$

Step 6: Contribution Measure

The measure of the contribution to implementing the industrialization strategies on each pre-selected construction system is related to *System Weighting* (Sw), the specific weight of the evaluated system in the project. For the present research, Sw is calculated based on the cost because construction companies use it in their usual practices to measure systems incidence. According to the above, Sw is defined by the equation (1).

$$\text{Sw} = \frac{\textit{System cost}}{\textit{Project}\ \text{direct}\ \textit{cost}} \quad (1)$$

The contribution of each pre-selected system is given in terms of the type of intervention (step 5). For construction systems related to standardization, the contribution measure is labeled as *System Standardization Index* (*SSTi*) and it is defined by the typological variability in the system.

$$SSTi = \text{TV}f * \text{Sw} \quad (2)$$

where:
TVf = Typological variability factor

If the Number of types = 1, then, TVf = 1; else, if, Number of types > 1, then,

$$\text{TV}f = \left(\frac{1}{\text{Number of types}}\right) * (1 + Rf) \quad (3)$$

For construction systems related to modular coordination, the contribution measure is labeled as *System Modular Coordination Index* (*SMCi*) and it is defined by the concentration of modular dimensions in the system.

$$\text{SMC}i = \text{MD}f * \text{Sw} \quad (4)$$

where:
MDf = Modular dimensions factor

$$\text{MD}f = \frac{\text{MD}}{\text{TD}} \quad (5)$$

where:
MD = Number of dimensions that adjust to the basic module or multiples.
TD = Total number of dimensions in the evaluated system.

For construction systems related to Preassembly, the contribution measure is labeled as *System Preassembly Index* (*SPAi*) and it is defined by the preassembly intensity of the system.

$$\text{SPA}i = \text{PA}f * \text{Sw} \quad (6)$$

where:
PAf = Preassembly factor: Intensity of the preassembly type of the evaluated system, according to Table 2.

Table 2. Preassembly factor according to the preassembly type

Level	Type	PA*f*
Level 1	Preassembled components and subassemblies	0.2
Level 2	Nonvolumetric preassembly	0.6
Level 3	Volumetric preassembly	0.8
Level 4	Modular Building	1

THE FRAMEWORK OF THE PROPOSED METHOD

The presented model is not oriented to the measurement of the general industrialization of a project but rather to the analysis of the potential of a construction system, in terms of the impact of its industrialization, on the general performance of the project. According to above, this is a method of comparative analysis in which the values resulting from the measurement of an individual system must be interpreted in reference to the values resulting from the evaluation of other systems.

The framework of the proposed method is presented in Figure 5.

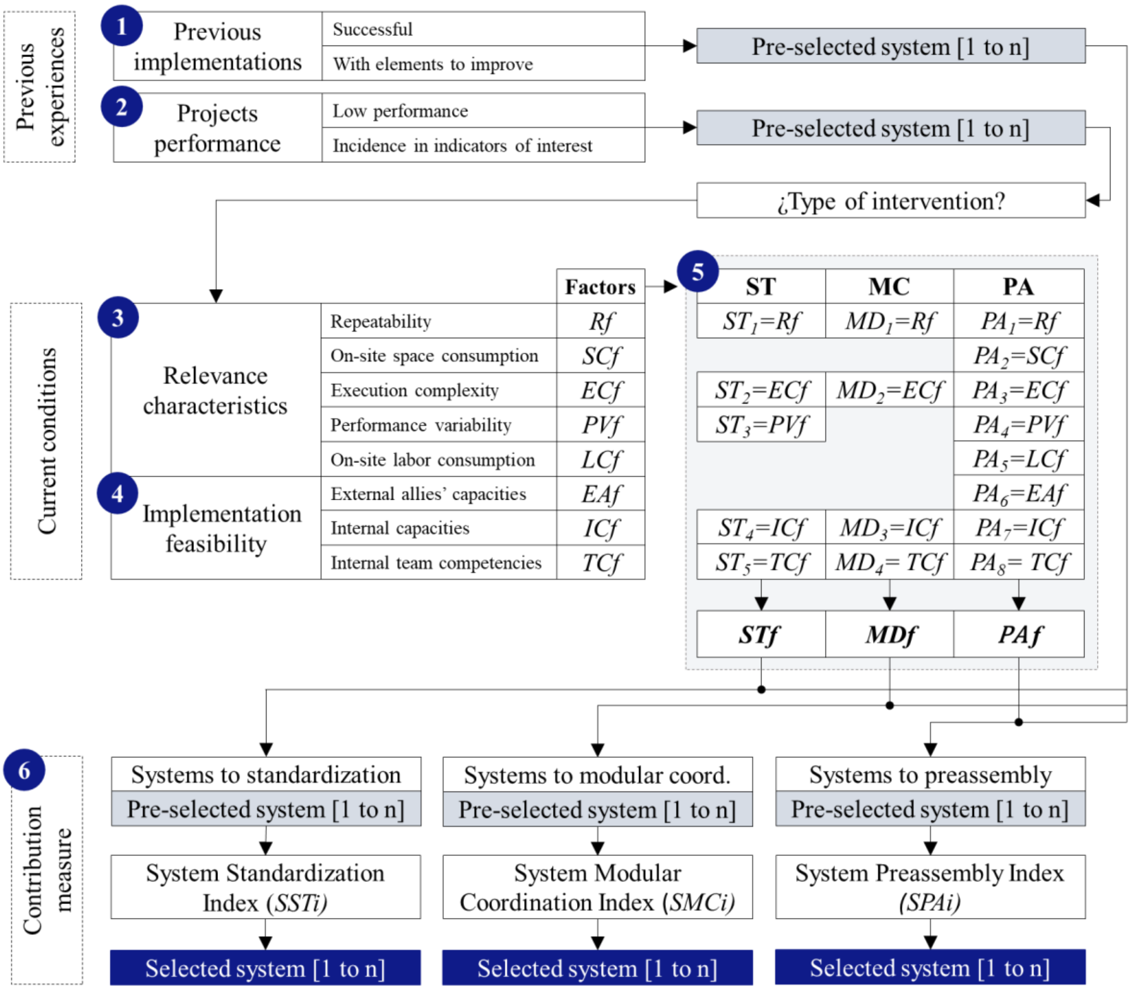

Figure 5. The framework of the proposed method

APPLICATION EXAMPLE

To illustrate how the model is implemented, its application in evaluating the window system of a specific project is presented below. Regarding said illustration, it is opportune to give the following clarifications: *(i)* Its scope is limited to illustrating the evaluation process of a system. It does not integrate the comparative analysis associated with the referencing among systems oriented to selecting the specific systems to intervene, based on their potential impact on project performance. *(ii)* Steps 1 and 2 of the method associated with Approach 1: Previous Experiences were not included in the illustration. Only Approach 2: Current Conditions is included, which is directly related to the proposed metrics, whose application is intended to provide clarity. (iii) Contribution measures are presented in two scenarios: actual and hypothetical—the hypothetical scenario results from the inclusion of changes in the evaluated system related to the industrialization strategies.

Window system information is presented in Table 3:

Table 3. Windows system information

Type	Quantity (un)	Dimension (m) X	Dimension (m) Y	Location	Specification
W1	103	0.8	1.5	Bedroom 1,2,3a	Fixed/sliding panel; clear
W1A	10	0.8	1.5	Bedroom 3b	Fixed panel; opaque
W2	28	0.8	1.5	Kitchen	Aluminium shutter + fixed/sliding panel; clear
W2A	9	0.8	1.5	Kitchen	Projecting panel in aluminum shutter; clear
W3	37	0.55	0.6	Bathroom	Aluminum shutter + fixed/sliding panel; opaque
W4	1	0.8	0.6	Garbage room	Fixed panel in aluminum shutter
W5	3	2.8	1.5	Living room	Two fixed and one sliding panel; clear
W6	1	0.8	0.3	Technical room	Fixed panel in aluminum shutter
W7	8	0.15	0.6	Electric shaft	Fixed panel in aluminum shutter
GD1	35	2.8	2.4	Living room	Two fixed and one sliding panel; clear

According to the above information and specific conditions of the project, the collaborative workgroup evaluated the Relevance characteristics and the Implementation feasibility factors (steps 3 and 4). Based on this, Standardization, Modular coordination, and Preassembly factors were calculated (step 5) (Figure 6).

		Affectation elements	Score	Factors
Relevance Characteristics	R	Repetitions (R_1)	1	$Rf = 1$
	SC	Space consumption (SC_1)	0.75	$SCf = 0.75$
	EC	Variety (EC_1)	0.75	$ECf = 0.50$
		Connectivity (EC_2)	0.25	
	PV	Cost variability (PV_1)	0.75	$PVf = 0.58$
		Time variability (PV_2)	0.50	
		Quality variability (PV_3)	0.50	
	LC	Intensity (LC_1)	0.75	$LCf = 0.75$
		Density (LC_2)	0.75	
Feasibility Elements	EA	Existing solutions (EA_1)	0.75	$EAf = 0.92$
		Supplier capacity (EA_2)	1	
		Transp. availability (EA_3)	1	
	IC	Production capacity (IC_2)	0.75	$ICf = 0.92$
		Financing capacity (IC_2)	1	
		Space availability (IC_3)	1	
	TC	Team competencies (TC_1)	1	$TCf = 0.87$
		Skilled workforce (TC_2)	0.75	

→

Factor	ST	MD	PA
R	1	1	1
SC			0.75
EC	0.50	0.50	0.50
PV	0.58		0.58
LC			0.75
EA			0.92
IC	0.92	0.92	0.92
TC	0.87	0.87	0.87
	$STf = 0.77$	$MDf = 0.82$	$PAf = 0.79$

Figure 6. Relevance characteristics and implementation feasibility evaluation

Contribution Measure (step 6)

Contribution measures are presented in two scenarios: real and hypothetical. The hypothetical scenario is the result of the inclusion of three changes: *(i)* reducing the number of window types from 10 to 4, *(ii)* passing the means on the X-axis of W3 and W7 to the upper multiple of the closest module, and *(iii)* moving from level 1 to level 2 of the preassembly, starting from proposing nonvolumetric preassembly, with the previous assembly of the wall-window interaction.

The results of the calculations associated with the indexes of system standardization, modular coordination, and preassembly are presented in figure 7. The project's direct cost is USD 275,445.79, and the windows system's cost is USD 19,446.73. Based on these values, the System Weighting (Sw) was calculated.

		Scenario	
	Affectation elements	**Actual**	**Hypothetical**
SW	Window System Weighting (*Sw*)	0.071	0.071
ST	Number of types	10	4
	Repeatability factor (*Rf*)	1	1
	Typological variability factor (*TVf*)	0.2	0.5
	System Standardization Index (*SSTi*)	0.014	0.036
MD	Total dimensions (*TD*)	470	470
	Modular dimensions (*MD*)	425	470
	Modular dimensions factor (*MDf*)	0.904	1
	System Modular Coordination Index (*SMCi*)	0.0642	0.071
PA	Preassembly factor (*PAf*)	0.2	0.6
	System Preassembly Index (*SPAi*)	0.014	0.043

Figure 7. Contribution measure

CONCLUSIONS

IPA provides concise data regarding two scales. *(i)* The state of the construction system, that is, the level of standardization, modular coordination, and preassembly of the system: Typological variability factor (*TVf*), Modular dimensions factor (*MDf*), and Preassembly factor (*PAf*). *(ii)* The system's capacity to contribute to the project based on standardization, modular coordination, and preassembly of the System: System Standardization Index (*SSTi*), System Modular Coordination Index (*SMCi*), and System Preassembly Index (*SPAi*).

IPA constitutes a comparative analysis tool. It provides an analysis of a line of different construction systems, from formal measurements and oriented to comparable results. To provide the construction industry with a systemic process that supports decision-making related to industrialization efforts, applicable in the early stages.

Systems weighting (Sw) is calculated based on the cost because construction companies use it in their usual practices to measure systems incidence. However, since a decrease in system cost decreases the system's weight in project direct costs, a desirable reduction (the system cost) would negatively affect the resulting index of *SSTi*, *SMCi*, and *SPAi*. Therefore, Sw must be calculated with the initial system cost, and its calculation must not be updated in improvement iterations. As a future line of work, it is recommended to calculate Sw related to a different variable.

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