

Article

Integrated Maturity Assessment of Manufacturing, Logistics, and Assembly in Off-Site Construction

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Abstract

Off-site construction (OSC) is recognized for its potential to improve productivity, quality, safety, and sustainability. However, these benefits are often not fully realized because manufacturing principles and their effects on subsequent stages remain insufficiently understood and managed as an integrated production system. In addition, OSC complexity creates the need for structured approaches that support implementation and progressive improvement. Existing approaches remain limited in their ability to jointly assess these interdependent processes, clearly define maturity progression, and provide an integrated basis for improvement. This study addresses this gap by developing an integrated maturity assessment for manufacturing, logistics, and assembly (MLa) in OSC. The research followed five-stages: comprehensive literature review, expert-based triangulation, AHP-based weighting, maturity-level conceptualization, and feasibility assessment through a case study. The proposed assessment comprises 7 variables and 56 indicators. The results show that workplace configuration management and process orientation are foundational dimensions, while capacities, management practices, and management capabilities enable MLa-operationalization, and sustainability and CITs applications represent advanced maturity conditions. The weighting structure was established using the Chilean AEC industry as the reference context, and the case study provided preliminary evidence of feasibility and applicability of the assessment in diagnosing maturity conditions and identifying improvement paths for integrated MLa-operations in a real OSC company.

Keywords: off-site construction; manufacturing factors; assembly factors; maturity model



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1. Introduction

Off-Site Construction (OSC) is regarded as a mass production process [1,2] in which a large part of the manufacturing operations is performed in a controlled environment (e.g., factory) where elements/modules are built, transported, erected, and assembled in their final location on site [3–5]. This is conducive to a more sustainable building construction method [6] by reducing waste and site labor, improving worker safety [2], quality [7,8], and productivity, increasing cost-effectiveness, and shortening construction

schedules [9]. However, the current state of the construction industry is characterized by a lack of understanding of OSC and its complexities, resulting in information gaps and inconsistencies across manufacturing, logistics, and assembly operations [10], inhibiting the ability to obtain the full OSC benefits [11].

The adequate adoption of manufacturing and assembly processes is essential to industrialization [12]. Buildings constructed using OSC methods can be approximately 20% to 70% more expensive than those delivered through traditional construction [13,14]. This increase is primarily associated with additional materials and work requirements, as the manufacturing and onsite assembly activities may account for approximately 32% to 63% and 25% to 50% of the incremental cost, respectively [13]. In parallel, logistics activities such as material transportation, order picking, material arrangement, and coordination across multiple trades can significantly affect OSC project performance. Previous studies have shown that element transportation alone may represent 10% to 20% of OSC costs [13,15]. Therefore, greater attention should be paid to the manufacturing, logistics, and assembly phase in OSC.

At the same time, improved management of manufacturing and assembly line operations can support OSC implementation and positively influence logistics performance within the production stage [10,12]. Research in the OSC field argued that the manufacturing and assembly process could improve productivity time by 12% due to reduced on-site activities [7] and achieve up to 24% cost savings [8]. Despite those advantages, the traditional construction setting prevails, and professionals still work under conventional processes and standards [16]. One of the main causes is the lack of knowledge [17] and understanding of the manufacturing principles of OSC [14,18,19]. To some extent, this scenario makes that OSC adoption remains low, particularly in developing countries [14,18], and leads to the presence of current hindrances to OSC uptake, such as the lack of management practices oriented to manufacturing requirements [16,20], lack of on-site management practices ad hoc to OSC methods [20,21], limited manufacturing capacities [5,22–24], and lack of builders capable of managing processes between factory and assembly operations [25–27].

To respond to these challenges and maximize OSC opportunities, two complementary lines of inquiry emerge that need to be addressed. First, there is a theoretical need to better understand the manufacturing process and its effects on subsequent stages [28] as part of an integrated production system within the construction ecosystem. Second, there is a managerial and methodological need for approaches capable of translating that understanding into structured mechanisms for managing OSC complexity and supporting its progressive adoption in practice [29,30].

From the first perspective, introducing Lean Construction (LC) practices is regarded as a suitable approach to support OSC adoption [31,32]. LC provides a relevant process-oriented basis, as it emphasizes waste reduction, workflow reliability, variability control, and the improvement of the production system as a whole [33–36]. This perspective is especially relevant to OSC, where manufacturing, logistics, and assembly are strongly interdependent. Although prior studies have shown that lean principles can support OSC adoption [37–39], the available evidence remains limited and is largely concentrated on case-specific applications [38] or local optimizations [32,37] that are often driven by a sense of urgency and aimed at addressing specific objectives [40,41], offering insufficient guidance for the systematic incorporation of LC into OSC-MLa management [11].

From the second perspective, the need for structured approaches to support OSC implementation has been increasingly recognized in the literature [29,30]. More broadly, OSC studies have examined manufacturing systems, logistics coordination, assembly management, technological support, and sustainability as critical dimensions of implementation. Within this context, the maturity model (MM) approach has been identified

as a well-established method for supporting OSC adoption, since it provides a framework to assess current capabilities [42,43], define progressive levels of development, and support improvement pathways for adopting new technologies or strengthening organizational capacities [43,44]. For instance, Wang et al. [43] developed an industrialized construction maturity model based on the European Foundation for Quality Management (EFQM) excellence model, structured around “enablers” and “results.” Razkenari et al. [42] proposed an MM to support the transition from conventional to industrialized construction. Bendi et al. [45] developed an OSC maturity model to assess practitioners’ readiness in the Indian market, focusing on operational challenges, execution strategy, planning, and efficiency. Similarly, Liu et al. [46] proposed an MM to assess supplier management maturity across procurement, operational efficiency, relationship coordination, strategy alignment, and corporate social responsibility. More recently, Cao et al. [47] developed a maturity model to assess BIM application in prefabricated buildings, defining five maturity levels and an evaluation system oriented to the progressive implementation of BIM in that context.

Although these models represent important progress, they still exhibit relevant limitations. In particular, they insufficiently capture the operational interdependencies among manufacturing, logistics, and assembly, as most approaches focus on a specific project phase, broad organizational readiness, supplier management, or the implementation of a particular technology. Additional limitations include restricted maturity-level conceptualization, limited incorporation of Lean Construction principles, and the lack of an integrated hierarchical weighting structure tailored to differentiate the relative importance of the assessment variables across MLa operations conceived as a single phase. In summary, the literature reveals a gap in integrated maturity models capable of assessing MLa as a single and interdependent OSC phase while also incorporating explicit conceptualization, variable hierarchy, and a clearer process-oriented perspective. To address this gap, this study develops a comprehensive OSC-MLa maturity model aimed at supporting companies in increasing their manufacturing, logistics, and assembly capacities through objective measures and well-defined guidance. The specific research objectives are:

1. Identify the MLa critical success factors for the effective adoption of OSC MLa practices and processes.
2. Determine the suitable variables and indicators for the OSC-MLa MM based on the OSC critical success factor review.
3. Determine the relative weights of the OSC-MLa variables and indicators.
4. Perform a complete conceptualization of OSC-MLa variables for each maturity level.
5. Implement the OSC-MLa MM and assess its structure in a real context through a case study.

The methodology supporting these objectives includes a comprehensive literature review, expert-based triangulation, AHP-based weighting, maturity-level conceptualization, and feasibility assessment through a case study. The study contributes to the OSC literature by proposing a structured OSC-MLa maturity model that provides a structured representation of the interdependence among manufacturing, logistics, and assembly, while providing a practical framework for managing OSC complexity and guiding the progressive improvement of MLa operations in the construction sector.

The remainder of the paper is structured as follows. Section 2 presents the research design and procedures adopted to develop and assess the OSC-MLa maturity model. Section 3 reports the model-development results and its application in the case study. Section 4 interprets the resulting hierarchy of maturity variables and discusses the model’s applicability in practice. Finally, Section 5 synthesizes the main conclusions, theoretical and practical contributions, limitations, and avenues for future research.

2. Research Methodology

The OSC-MLa MM was developed through five sequential stages, comprising both quantitative and qualitative research methods, in which the findings from each stage informed the subsequent ones (Figure 1). The five sequential stages are: (i) identification of the MLa Csf that comprises the OSC-MLa MM evaluation system, (ii) validation of variables and indicators of the evaluation systems, (iii) determination of the weight among OSC-MLa variables and indicators, (iv) design and validation of OSC-MLa maturity levels, (v) feasibility assessment of the OSC-MLa MM in real context: a case study.

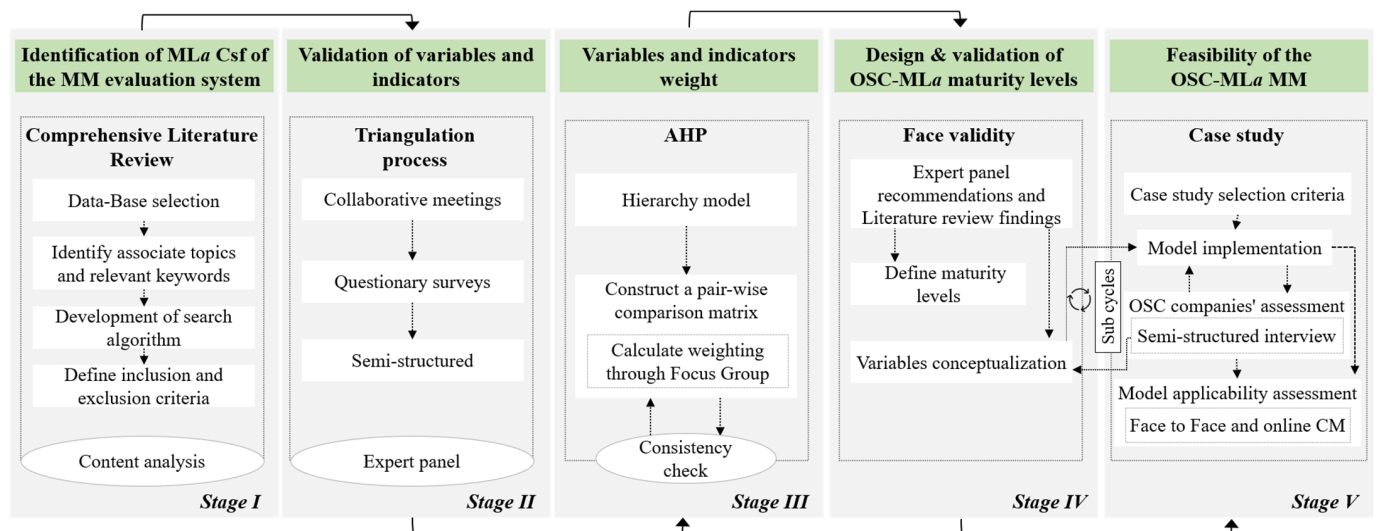


Figure 1. Research method.

2.1. Identification of the OSC-MLa Critical Success Factors

2.1.1. Comprehensive Literature Review

Lean Construction provides an important process-oriented lens for understanding and improving MLa interdependencies, while maturity models provide a structured mechanism for assessing and guiding development. The model itself, however, is informed by a broader body of OSC literature addressing manufacturing, logistics, assembly, technology, and sustainability. Therefore, consistent with other studies in the OSC field, the first step of the research method was to conduct a comprehensive literature review (CLR) to identify the critical success factors (Csf) affecting the adoption of MLa practices and processes [6,48]. A comprehensive literature review supported the build-up of a theoretical understanding of the topic. It formed a solid basis for preparing instruments for reliable data collection [49]. To ensure broader coverage, the authors selected recognized databases such as Scopus and Web of Science, as well as specialized journals, conference papers, books, and industry reports. Initially, the authors used the title/abstract/keyword functionality of the database search engine to query multiple topics and keywords. The topics included were “Off-site construction,” “manufacturing, logistic and assembly factors,” “Maturity models,” and “Maturity models in OSC.” For these topics, a list of keywords was selected to inform search algorithms.

Three research algorithms were developed. The first aimed to identify the Csf associated with MLa practices and processes; the second, to review the incorporation of Lean Construction into OSC; and the third, to examine MLa-related Csf in current OSC maturity models and related approaches. The first research algorithm (Ra) included: (“Off site construction” OR “Off-site construction” OR “Offsite construction” OR “Off-site production” OR “Offsite production” OR “modular construction” OR “modular integrated construction” OR “prefabricated prefinished volumetric construction” OR “modern method of

construction" OR "Prefabricated building" OR "Industrial* building system" OR "Industrial* building" OR "Industrial* housing" OR "Industrial* Construction" OR "Precast") AND ("Fact*" OR "Critic*" OR "Best practic*" OR "critical success factor*" OR "learned lesson*" OR "success factor*" OR "key element*" OR "Strateg*") AND LIMIT-TO LANGUAGE ("English").

For the second and third *Ra*, the OSC keywords of the first *Ra* were added in the second and third *Ra* with their respective keywords. The second *Ra* incorporated Lean Construction-related keywords, including: ("Lean Construction" OR "Lean Production" OR "Lean tools" OR "Lean"). The third *Ra* incorporated maturity-model-related keywords, including: ("maturity model" OR "maturity" OR "model capability" OR "maturity grid" OR "maturity assessment"). Across the three research algorithms, the initial title/abstract/keyword search returned a large number of records that were broadly related, many of which were not sufficiently aligned with the scope of this study. Therefore, the search was subsequently restricted to the title field to improve precision and relevance.

The selection of articles was based on inclusion/exclusion criteria. The main inclusion criteria involved (i) documents that explicitly discuss the topic OSC in implementation environments (e.g., case studies, pilots) or systematically discuss MLa application; (ii) documents that explicitly discuss the Lean Incorporation into OSC ecosystem (iii) articles that are published in a peer-reviewed journal or conference papers; (iv) Books and industry reports developed by recognized research or industry entities.

Additionally, the structured database search was complemented by backward and forward citation searching to improve literature coverage [50]. In practice, this involved examining the reference lists of the included studies and identifying articles that cited them, using the initially selected papers as the basis for additional retrieval. The process was repeated until no further relevant studies were found, thereby complementing the first draft of the OSC-MLa MM evaluation system.

The numerical outcomes of the identification, screening, eligibility assessment, citation searching, and update-search stages are reported in Section 3.1.1 and summarized in the article protocol selection in Appendix A (Figure A1).

2.1.2. Qualitative Content Analysis and Synthesis of MLa Critical Success Factors

Using the final corpus of documents, the researchers conducted an in-depth review through an inductive qualitative content-analysis procedure to transform the literature-derived MLa critical success factors into the preliminary structure of the OSC-MLa evaluation system. This method enables concepts to be systematically derived from textual data through coding, categorization, and abstraction into a higher-order conceptual structure [51] and has been applied in construction research to organize heterogeneous literature-derived concepts into thematic clusters and broader analytical frameworks [52]. The extracted critical success factors constituted the units of analysis and were initially coded according to their substantive meaning and operational relevance to manufacturing, logistics, and assembly. Conceptually equivalent or synonymous codes identified across the reviewed sources were harmonized under common terminology, while redundant content was consolidated to minimize duplication and double counting. Specific and assessable practices, capabilities, resources, technologies, and organizational conditions were classified as indicators. Related indicators were subsequently grouped and abstracted into higher-order categories representing the broader variables of MLa maturity. Where a factor was relevant to more than one category, it was assigned to the variable that best reflected its primary evaluative purpose. Constructs that duplicated existing content, lacked sufficient specificity for operational assessment, or fell outside the defined MLa scope were merged

or excluded. The resulting preliminary structure was subsequently reviewed and refined through the expert-triangulation process.

2.2. Validation of Variables and Indicators

Triangulation was adopted to validate the variables and indicators that comprise the OSC-MLa MM evaluation system. The triangulation approach offered researchers a wider view and analysis from different perspectives, employing different methods to generate more consistent and convergent outcomes [53]. In this research, triangulation included the following steps: (a) collaborative meetings, (b) questionnaire surveys, and (c) semi-structured interviews.

2.2.1. Setting up an Expert Panel

To conduct a rigorous triangulation process, the authors invited experts with verifiable experience in OSC to participate in the study, specifically in manufacturing, logistics, and assembly operations. The judgment of qualified voices (experts) is a good strategy to verify the research content [54] and avoid subjectivity in the outcomes [16]. Consequently, the authors established an expert panel. The main objective of establishing an expert panel is to obtain an unbiased, representative sample [55]. To this end, the criteria established for the selection of each expert were: (i) at least five years of experience in the AEC industry, (ii) an advanced degree in the field of civil engineering, and (iii) active participation or membership in private/public cohesive entities that promote OSC.

Regarding the panel size, no study has found a significant correlation between the number of experts and the effectiveness of the outcomes [55]. Following current literature recommendations, 20 experts were invited to participate [18,56]; 16 accepted to form part of the triangulation process, and at least 5 participated in each triangulation step [57]. The experts willing to participate in this study are national and international academics and professionals who are associated with entities such as the Industrialized Construction Council of Chile (CCI), Precast Concrete Institute (PCI), Glass National Association, National Accreditation & Management Institute (NAMI), International Group of Lean Construction (IGLC), Research Network of the Research Centre of Excellence of Production of the *Universidad Catolica de Chile* (GEPUC), Interdisciplinary Center for Productivity and Sustainable Construction of the *Universidad Catolica de Chile* (CIPYCS), Chilean Ministry of Housing (SERVIU), and national (I_{NOSC_c}) and international off-site construction companies (I_{NOSC_c}). Table 1 shows the expert's profiles.

Table 1. Profile of the Experts who Validated the OSC-MLa Key Factors.

Ex	Degree	Field of Work	Affiliation	YE
1	Architect, MSc	OSC management; LC and Sustainability	CCI, GEPUC, IGLC	11–15
2	Civil Engineer, PhD	OSC management; LC and BIM	CCI, CIPYCS, IGLC	11–15
3	Architect, MSc	OSC management; Sustainability	CCI	16–20
4	Civil Engineer, PhD	PM and LC	CCI; GEPUC	16–20
5	Civil Engineer, PhD	OSC management; LC and Sustainability	IGLC, I_{NOSC_c}	>20
6	Civil Engineer, MSc	OSC management and LC	CCI; GEPUC, IGLC	6–10
7	Civil Construction, MSc	OSC management and Sustainability	CCI, N_aOSC_c	16–20
8	Structural Civil Engineer, PhD	OSC design and MAs	PCI; I_{NOSC_c}	6–10
9	Structural Civil Engineer, MSc	OSC management and MAs	NAMI; I_{NOSC_c}	6–10
10	Civil engineer, Sp	OSC management and T&I	MINVU	16–20

Table 1. Cont.

<i>Ex</i>	Degree	Field of Work	Affiliation	<i>YE</i>
11	Civil Engineer · MSc	OSC management and MAs	CCI, I _N OSC _C	16–20
12	Civil Construction, MSc	OSC management and T&I	CCI; N _a OSC _C	6–10
13	Civil Construction, MSc	MAs and OSC design	CCI; I _N OSC _C	6–10
14	Civil Construction, Sp	OSC management and Mas	CCI; N _a OSC _C	>20
15	Civil Construction, Sp	PM and OSC management	CCI	16–20
16	Civil Engineer, Sp	PM, OSC management and MAs	CCI	>20

Ex = Expert; *YE* = Years of experience; *Sp* = Specialization; *PMa* = Project manager; *TM* = Technical Manager; *PM* = Project management; *LC* = Lean Construction; MAs = Manufacturing and assembly operations; T&I = Technology and Innovation; CEO = Chief Executive Officer.

2.2.2. Collaborative Meetings, Questionnaire Surveys, and Semi-Structured Interviews

Collaborative meetings (CMs) foster an environment of learning and knowledge sharing among participants [58]. Three 60 min meetings were scheduled to carry out the CM, and a group of five experts (*Ex*₁–*Ex*₄ and *Ex*₆) agreed to participate. The main objective of the collaborative meetings was to review the structure of the preliminary OSC-MLa MM evaluation system, including the proposed variables, their order, and associated indicators. In addition, the first proposal to set up the questionnaire survey emerged from those collaborative meetings.

The questionnaire survey has been recognized as an effective method for collecting elemental data on industry perspectives in the off-site construction field [22]. It included introductory information about the project (e.g., description of objective and key concepts); Section One (*I*) aimed to collect profile information, and Section Two (*II*) aimed to measure the agreement level about the proposed OSC-MLa variables, indicators to measure MLa maturity in OSC, and if each variable was well defined and represented the indicators that comprised it. In Section Two, an open question was added, asking respondents whether they would incorporate new variables or indicators if necessary. The agreement level was measured using a 5-point Likert scale (e.g., 1 = very low agreement, 5 = very high agreement). The authors used the mean value (Mv) to assess agreement. An Mv has been employed extensively in the construction field to measure agreement among participants [59,60] to rate factor significance [21,61], and to examine perceptions [22]. Finally, in collaboration with the research center GEPUC, the questionnaire survey was prepared on the SurveyMonkey platform and sent by email to the panel of experts, resulting in 8 fully completed questionnaires (*Ex*₅–*Ex*₁₃).

The semi-structured interviews constituted the final step of the triangulation process. In this stage, seven experts with extensive professional experience in OSC-MLa were intentionally selected *Ex*₇–*Ex*₉, *Ex*₁₁, *Ex*₁₃ and *Ex*₁₅–*Ex*₁₆. Most of these experts had participated in the questionnaire survey and were included to provide a deeper understanding of the ratings assigned to each variable and indicator, as well as their relevance to the current AEC industry context. The remaining experts were selected because of their recognized industry background in incorporating OSC practices and processes into construction projects. This third validation step added rigor to the triangulation process and further supported the validity of the variables and indicators comprising the OSC-MLa MM evaluation system.

2.3. Weighting the Variables and Indicators Through AHP

Each variable supports the companies' path to increase the maturity adoption during the OSC-MLa phase. Therefore, it is mandatory to identify its weight within the maturity evaluation system [62] and define the weighting of one variable over another [43]. To this

end, the AHP was employed to prioritize the variables [63]. Prof. Thomas Saaty developed this multi-criteria method in the 1970s. Nowadays, the AHP is the most frequently used multi-criteria technique [64]. Previous studies in the construction field have reported successful experience applying this method [43,62,65] due to its effectiveness in supporting qualitative analysis with quantitative measurements [66]. Recognizing that some variables and indicators may be context-sensitive, the AEC Chilean industry was used as a testing context to apply the AHP approach, due to its current gained experience adopting OSC in different fields such as: mining, residential, and industrial sectors [67], and its rapid growth in its infrastructure that holds promise for a massive OSC implementation in the short term [16].

The AHP method consists of (i) organizing in a hierarchical structure a set of variables and indicators (e.g., criteria, sub-criteria) and (ii) constructing the judgment matrix to perform a pairwise comparison among them, which relies on the judgments of experts [66,68]. The comparison is made using a numerical scale ranging from 1 to 9, representing how much more one variable dominates over another [64,68]. Then (iii) the consistency ratio (CR) is calculated (eq. $C.R = CI/RI$) [43,69]. A consistency ratio of 0.1 or less was guaranteed to yield an informed expert judgment [69]. Finally, the variables' weights were calculated using steps (i) to (iii) for each variable that comprised the evaluation system.

In this research the authors conducted the AHP with five experts (Ex_6 to Ex_{10}) across four 90 min focus group sessions. Each of the five experts completed an individual pairwise comparison matrix for the seven variables. The matrices were combined using the aggregation of individual judgments approach, in which corresponding pairwise judgments were aggregated through the geometric mean, with equal weight assigned to each expert. The priority vector of the resulting consolidated matrix was then derived using the eigenvector method. Consistency was assessed for both the individual and consolidated matrices using the consistency ratio. The individual and consolidated pairwise comparison matrices are provided in Appendix A (Tables A1 and A2). Figure 2 shows the AHP.

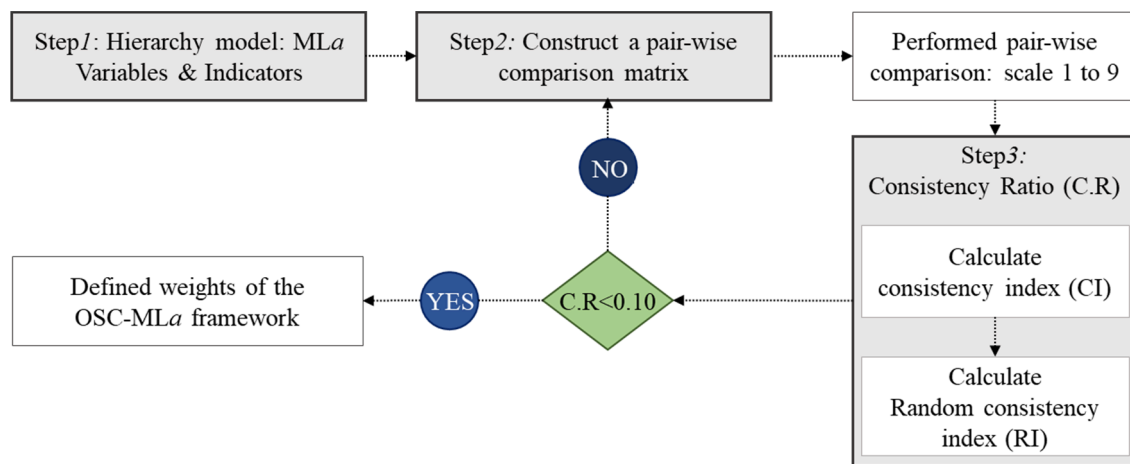


Figure 2. AHP.

Regarding indicator-level weights, the AHP-derived weight of each variable was distributed equally among its indicators, with each local weight calculated as the reciprocal of the number of indicators comprising the variable. This decision was based on two main criteria. First, the literature review and triangulation process had already established the relevance and content validity of the indicators included in the model. Second, extending the AHP to the indicator level would have required 222 additional pairwise comparisons, substantially increasing the burden on the experts and the difficulty of maintaining consistent judgments [70,71]. Equal weighting at lower hierarchical levels has been recognized in

building assessment methodologies as a transparent approach that reduces the number of pairwise comparisons while retaining expert-derived weights at the higher criterion level [72]. Equal local weighting was therefore adopted as a transparent baseline that avoided additional preference elicitation and potential response error. Since this approach represents a simplifying assumption rather than an assertion that all indicators are intrinsically equivalent in importance, its influence on the case-study diagnosis was examined through sensitivity analysis [73]. Although the indicators were not individually weighted through AHP, they remained integral to the variable-level pairwise comparisons. The experts evaluated each variable based on its definition and complete set of indicators, which clarified its scope and evaluative orientation during the judgment process.

2.4. Design OSC-MLa Maturity Levels and Variables Conceptualization

The Maturity Model demonstrates companies' capacity to achieve desirable outcomes (e.g., increase the maturity of a subject) [45,74]. This assessment was undertaken through maturity levels defined to measure the evolutionary characteristics [74]. Similar maturity models have defined 3 to 5 levels [43,45,46]. A maturity model's main contribution lies in clearly describing the path toward higher maturity levels [31,44]. In this sense, conceptualization refers to the definition of maturity levels for each variable comprising the OSC-MLa MM and is considered a critical aspect of maturity model configuration because it provides explicit guidance for progression across levels [44]. The authors used information extracted from CLR, the triangulation process, and the AHP method to ensure a well-covered conceptualization. All these approaches generated theoretical and practical explanations about the implications of adopting MLa variables. Figure 3 shows a conceptual representation of the OSC-MLa MM.

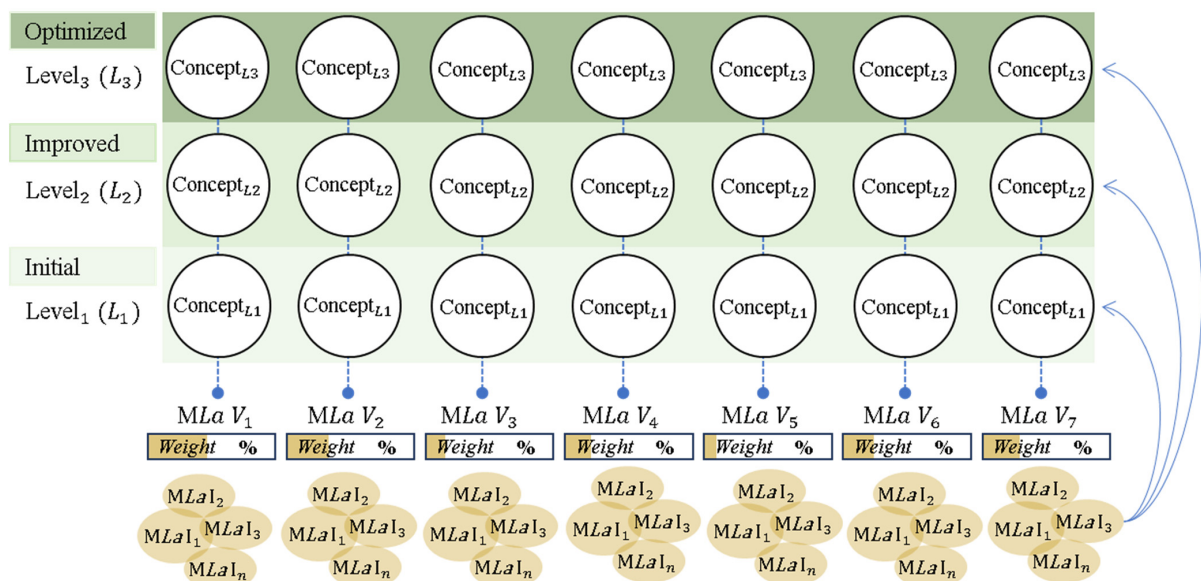


Figure 3. Conceptual representation of the OSC-MLa.

The authors employed face validity to validate the maturity levels and conceptualizations. Face validity is based on expert input regarding the correctness and reasonableness of the constructed model (e.g., OSC-MLa MM) [75,76]. To this end, the researchers presented the model with the latest updates (e.g., variables and indicators), maturity levels, and conceptualization to four experts (*Ex₅–Ex₇* and *Ex₉*) from the panel of experts. Their feedback was obtained through face-to-face and virtual collaborative meetings. During the face validity, an iteration loop between stages IV and V took place. The case study began, and in the meantime, some findings were collected; the authors made minor adjustments

to the variables' conceptualizations, which were subsequently discussed and approved in both scenarios (with the experts and case study professionals). This enriched the validation process and generated two sub-cycles for refining the model, helping to generalize or make the descriptions precise when required.

2.5. Feasibility Assessment of the OSC-MLa MM

The case studies are useful for verifying the feasibility of the system developed (e.g., OSC-MLa MM) in real scenarios [77]. The OSC-MLa MM was tested through an iterative process spanning stages IV and V at an OSC company in the AEC Chilean industry. The company participated in the entire delivery process and was selected for its market trajectory and recognition, as well as its proven record in the construction sector. These characteristics ensure that the entire model can be successfully applied in the case study. The application of the model was aimed at (i) assessing the maturity level of the case-study company and (ii) obtaining preliminary evidence of the model's feasibility and applicability in a real organizational context. The maturity level assessment was conducted through semi-structured interviews. The authors developed a questionnaire based on the variables and indicators that comprise the model, including questions on maturity-level characteristics for each variable, which guided the researchers in understanding the extent to which the company adopted each variable. The assessment was complemented by an on-site plant visit that enabled direct observation of the manufacturing process and review of selected company production data.

Because each variable was operationalized through its corresponding indicators, the maturity scores were assigned at the indicator level using the three maturity descriptions defined in the model: 1 = Initial, 2 = Improved, and 3 = Optimized. For each indicator, the evaluator compared the evidence obtained from the semi-structured interviews with the corresponding maturity-level descriptors. Interview statements were triangulated, where possible, with direct observations made during the plant visit and with operational information provided by the company. The resulting scores were subsequently discussed with the research team and company professionals to verify their alignment with the evidence collected. The agreed indicator scores were then aggregated using the local indicator weights and the AHP-derived variable weights to calculate the variable scores and the overall OSC-MLa maturity score.

The model applicability evaluation was conducted immediately after the maturity assessment. It was done through an online collaborative meeting with professionals who participated in the maturity assessment process. The authors had the opportunity to receive professional feedback and discuss it, gaining insights and making minor adjustments to the model. The criteria to guide the discussion were regarding (i) the quality of the information, (ii) completeness of the information in terms of variables, indicators, and maturity level descriptions, (iii) accuracy of the weighting of each variable into the evaluation system, (iv) model predictability capacity, (v) clarity of maturity level descriptions, (vi) implementation practicability, and (vii) usefulness of the OSC-MLa MM. Additionally, a questionnaire was constructed to rate, on a 5-point Likert scale, the extent to which the criteria were achieved. This approach provided preliminary qualitative and quantitative evidence regarding the model's feasibility and applicability in the case-study context.

3. Results

3.1. MLa Variables and Indicators to Measure Maturity Adoption in OSC-Design: Literature Review and Triangulation Process

The outcomes of the comprehensive literature review and triangulation process were the categorization of the MLa Csf into 7 variables and 56 indicators. The 7 variables are

described as (i) Manufacture and assembly workplace configuration management for optimization, flexibility, and standardized workflow, (ii) Capacities to support manufacturing, logistics, and assembly phases, (iii) Management practices for reliable and optimized manufacturing, logistics, and assembly processes, (iv) Management capabilities for reliable and optimized manufacturing, logistics, and assembly processes, (v) Manufacturing, logistics, and assembly as a process-oriented approach, (vi) Sustainable manufacture, logistics, and assembly approach, (vii) Construction Information Technologies (CITs) applications to support the manufacturing, logistics, and assembly operations. Table 2 shows the OSC-MLa variables and indicators that comprise each variable.

Table 2. OSC manufacturing, logistics, and assembly variables (MLa_v) and indicators (MLa_i).

MLa_v 1 Manufacture and Assembly Workplace Configuration Management for Optimization, Flexibility, and Standardized Workflow	Fr	Source
MLa _i 1.1 Organization assurance of the manufacturing and assembly workplaces based on the 5S approach (e.g., clean and ordered workplace, fixed and right place for material/tools, oriented to minimize worker/equipment movements).	5	[37,78–81]
MLa _i 1.2 Logistics plans for material flow and storage that adapt to multiple changes in workplace settings.	1	[78]
MLa _i 1.3 Workplace configuration considering defined repetitive tasks (e.g., stability and standardization).	5	[37,78–81]
MLa _i 1.4 Crews' activities and workflow are balanced (e.g., based on workload, material availability, workforce, machinery, etc.) and synchronized with workplace configuration alternatives.	3	[11,38,78]
MLa _i 1.5 Workplace layout that supports both product fabrication and assembly.	3	[25,35,79]
MLa _i 1.6 Workplace configuration considering workers' safety (e.g., safety instruction regarding materials and tools employed in each workstation, lifting safety).		Questionnaire
MLa_v 2 Capacities to support manufacturing, logistics, and assembly phases		
MLa _i 2.1 Flexible factories for manufacture and assembly (e.g., Factory-machinery capable of working with different materials, performing different kinds of tasks and sequences).	3	[37,82,83]
MLa _i 2.2 Reconfigurable factory layout for manufacture and assembly (e.g., modify task sequences via software, physical reconfiguration of machines/tools)	2	[82,83]
MLa _i 2.3 Capacity to have reliable supply relationships (e.g., stable relationships that guarantee supply and technical compliance) to maintain workflow continuity (e.g., manufacturing operations continuity).	2	[27,78]
MLa _i 2.4 Logistic system capable of determining the past states (tracing) of the elements/modules (e.g., location, custodian, condition, weather exposition, and external force).	2	[26,84]
MLa _i 2.5 Efficient and effective internal logistics to arrange materials and facilities for manufacture and assembly (e.g., monitor inventory, top up, and deliver materials efficiently and effectively).	3	[12,25,84]
MLa _i 2.6 Flexible team capacity (e.g., multifunctional workers adaptive to changing needs).	3	[78–80]
MLa _i 2.7 Temporary/mobile factory deployed on-site as needed.	4	[82,83,85,86]
MLa_v 3 Management practices for reliable and optimized manufacturing, logistics, and assembly processes		
MLa _i 3.1 Visual management for monitoring and control of manufacturing, logistics, and assembly (e.g., transparent disclosure of measuring performance).	4	[37,78–80]
MLa _i 3.2 Predictable task time preparation for manufacturing and assembly activities (e.g., implementing LPS and communicating at the previous start of production).	4	[37,78,87,88]
MLa _i 3.3 Frequent productivity tracking and management for manufacturing and assembly operations.	1	[25]
MLa _i 3.4 Preparing manufacturing and assembly sites to reduce difficult workflow setups and changeovers (e.g., one method to another).	3	[78,82,89]
MLa _i 3.5 Routine readiness and urgency assessment for production (e.g., off-site and on-site) to shortlist, start, and release production.	2	[84,90]
MLa _i 3.6 Regular implementation of an integrated and flexible materials/equipment management program (e.g., drawing bills of materials in sync with OSC strategy).	1	[25]
MLa _i 3.7 The supply chain is oriented to comply with codes and quality standards, determined by industry regulations or quality standards developed by the company as a regular practice.	3	[25,89,91]
MLa _i 3.8 Manufacturing process awareness by team members (e.g., workers who understand their responsibility for their own tasks and the effect of their decisions on OSC strategy).	3	[28,79,80]
MLa _i 3.9 Early assurance and understanding of the logistic plan for MLa (e.g., durations, technology, and regulatory constraints).	1	[25]
MLa _i 3.10 Maneuvering and route study for transporting structural/component elements or modules from the production plant to the assembly point (e.g., avoid road obstacles, permitted heights, detours, travel distance, sizes, and load requirements for transportation and assembly).		Questionnaire
MLa _i 3.11 Preparing just-in-time (JIT) logistic plan in line with off-site production and on-site requirements (e.g., timely and accurate plans).	5	[25,26,84,87,90]
MLa _i 3.12 People cross-training oriented (e.g., to get multi-skilled resources) for manufacturing, logistics, and assembly.	4	[11,39,78,88]
MLa _i 3.13 Concurrent engineering approach to support MLa (e.g., collaborative systematic scheduling).	3	[25,85,92]

Table 2. Cont.

MLa_v 4 Management capabilities for reliable and optimized manufacturing, logistics, and assembly processes		
MLa _i 4.1 Availability and experienced team assurance to support OSC business development.	3	[25,43,82]
MLa _i 4.2 Proper data collection for measurements (e.g., material waste, safety, cost, time) and performance analysis (e.g., a rapid and practical estimation tool for performing analysis).	6	[11,26,37,78,93,94]
MLa _i 4.3 Proficiency in implementing a planning system oriented to minimizing WIP, proper use of buffer size and location, and pull scheduling.	7	[39,78,87,90,92,93,95]
MLa _i 4.4 Capability to manage off-site and on-site production synchronization (e.g., to meet with supplying times) and work issues among manufacturing plants, logistic operations, and assembly site (e.g., risk, variability, unpredictability events, technical issues, material shortage).	9	[25–27,32,43,87,90,92,96]
MLa _i 4.5 Capacity to employ the OSC method with the conventional in situ method in a collaborative manner.	1	[85]
MLa _i 4.6 Means and capacities to perform product quality control (e.g., quality traceability, control tolerance/dimensional specifications) for manufacturing, logistics, and assembly.	3	[25,39,91]
MLa _i 4.7 Quality leadership to encourage a sense of workers' responsibility for quality.	3	[39,78,79]
MLa_v 5 Manufacturing, logistics, and assembly as a process-oriented approach		
MLa _i 5.1 Off-site construction as a strategic business approach that involves all parties rather than an alternative construction method per se (e.g., off-site incorporation in the overall project process).	1	[28]
MLa _i 5.2 Organized work based on transversal processes from project to project.	1	[97]
MLa _i 5.3 Systematic view of process for improvement rather than any ad hoc individual task improvements.	1	[37]
MLa _i 5.4 System with bidirectional information flow process (e.g., among manufacturers and builders).	3	[26,52,90]
MLa _i 5.5 Processes-oriented to maintain continuity of off-site operations and construction on-site.	2	[85,92]
MLa _i 5.6 Production process-balanced by reducing waste (e.g., over-processing or under-processing in workstations, congested work areas) and variability.	2	[11,85]
MLa _i 5.7 Response code to defects (e.g., solve problems based on deep analysis and spread and standard solutions to others).	4	[78–80,89]
MLa _i 5.8 Continuous improvement and accurate quality control routine (e.g., identify root causes of waste, prevent defects from proceeding in the process) for MLa efficiently and effectively.	6	[11,37,39,79,80,98]
MLa _i 5.9 Decision-making processes based on strategic preferences (e.g., technical grounds and business relationships) and logistic tasks (e.g., fleet management, loading schemes, and previous/current statistical analysis).	4	[27,84,88,99]
MLa_v 6 Sustainable manufacture, logistics, and assembly approach		
MLa _i 6.1 Efficient use of resources (e.g., minimize waste, traditional wet trades optimization off-site, such as plastering and masonry, material efficient use).	5	[43,85,89,92,100]
MLa _i 6.2 Efficient transportation of elements/modules (e.g., the route with fewer stops to save gas and avoid traffic, the route that allows more cargo shipment).		Questionnaire
MLa _i 6.3 Efficient use of heavy machines to reduce environmental effects for assembly operations (e.g., use the same rigging and hooks to avoid unnecessary changeovers or stopping, optimize the work heavy machine area to minimize time used to prepare the site).		Questionnaire
MLa _i 6.4 Manufacturing, logistics, and assembly processes are oriented to social safety (e.g., environmental protection, avoiding water pollution, and community disturbance).	3	[43,82,85]
MLa_v 7 CITs applications to support the manufacturing, logistics, and assembly operations		
MLa _i 7.1 Tracing and tracking materials/equipment in real-time, supported by CITs (e.g., RFID, GPS, Bluetooth-based sensors) along the supply chain from production plants to the site.	6	[26,52,81,84,101,102]
MLa _i 7.2 Digitalization (e.g., ITs combined with cloud computing) to improve real-time communication, integration, synchronization, and coordination through the supply chain.	2	[87,95]
MLa _i 7.3 BIM-based material procurement organization to support and improve supply chain management (e.g., to manage synchronization of supply chain, visualization of the status quo of material flow).	2	[47,52]
MLa _i 7.4 Modeling of assembly logistic plan design before the assembly to ensure and optimize the on-site layout (e.g., adequate spaces for unloading materials/products/equipment and free flow traffic around the site).		Questionnaire
MLa _i 7.5 Advancing models or algorithms (e.g., genetic algorithm, Ant Colony Algorithm) to assist in the development of optimal plans and schedules for production.	3	[32,37,84]
MLa _i 7.6 Standardization of elements/modules production assisted by BIM (e.g., 3D instruction for production).	2	[84,103]
MLa _i 7.7 Recording information and tracking of the elements/modules and operators' statuses assisted by CITs (e.g., RFID).	2	[84,101]
MLa _i 7.8 Site management optimization supported by BIM (e.g., detecting elements/modules' current status, material/equipment, and worker distribution).	4	[47,52,84,101]
MLa _i 7.9 Auxiliaries' technologies (e.g., cameras, drones, data capturing) to support on-site construction management and capture real-time information.	3	[84,101,104]
MLa _i 7.10 CITs oriented to control safety issues and risks (e.g., use of physiological sensors and RFID to monitor workers and work conditions, respectively) in advance.	2	[84,101]

Fr = Citation frequency; MLa_v = Manufacturing, logistic and assembly variable, MLa_i = Manufacturing, logistic and assembly indicator; Source = Authors who mentioned the indicator-related.

3.1.1. Main Variables and Indicators for Supporting Processes and Management

The authors screened the titles of 595 sources (e.g., articles, conference papers, and books), comprising 497 records identified through first *Ra*, 87 through Second *Ra*, and 11 through third *Ra*, resulting in a list of 150 records retrieved for detailed assessment. Then, based on the criteria established, reviewed topic (e.g., abstract review), the relevance of the journal and editorial, and impact (e.g., number of source citations), 116 records were excluded and 34 sources were retained from database searching. Backward and forward citation searching then identified eight additional eligible sources, resulting in a final list of 42 sources from which the variables and indicators for the OSC-MLa evaluation system were selected (Appendix A—Figure A1). The average frequency of citation of the indicators was three (3). This relatively moderate frequency suggests that, while the identified factors are consistently recognized across the literature, they are not uniformly consolidated within a single theoretical or methodological framework. This dispersion reflects the still-evolving nature of OSC research, particularly in integrating manufacturing, logistics, and assembly into a unified production system. Consequently, the absence of highly dominant indicators underscores the need for a structured maturity model that can synthesize and integrate these fragmented contributions into a coherent assessment framework.

A limited number of indicators exhibited higher citation frequencies, most notably those associated with planning systems and production synchronization (e.g., $MLa_i4.4$ and $MLa_i4.3$), indicating an emerging consensus in the literature regarding the critical role of coordination and planning capabilities in OSC performance. These indicators are frequently emphasized because they directly address the alignment challenges between off-site manufacturing and on-site assembly operations, which have been identified as key constraints in OSC systems [87,92]. Building upon these observations, the identified variables can be interpreted as interrelated dimensions of maturity that emerge from the progressive OSC systems, rather than as isolated constructs. The structure of the seven variables reflects a layered configuration in which foundational production principles, enabling organizational capabilities, and advanced performance-oriented systems coexist and evolve jointly.

First, variables such as manufacturing and assembly workplace configuration management (MLa_v1) and MLa as a process-oriented approach (MLa_v5) emerge as foundational dimensions. Their prominence in the literature is strongly associated with the principles of lean production and industrialized construction, where workflow stability, standardization, and system-wide process integration are considered prerequisites for performance improvement [37,39,105]. In particular, indicators related to workplace organization, such as the implementation of the 5S approach ($MLa_i1.1$) and standardized repetitive task configuration ($MLa_i1.3$), are particularly relevant due to their direct impact on reducing variability and enabling reliable production flows. These findings are consistent with prior studies that emphasize that early-stage OSC efforts must focus on establishing controlled, reproducible production environments before introducing more advanced practices [11,78].

Similarly, the relevance of MLa_v5 is explained by the growing recognition that OSC should be approached as a strategic, process-driven production system rather than a collection of isolated techniques [28]. Indicators such as continuous improvement routines ($MLa_i5.8$) and bidirectional information flow process across stakeholders ($MLa_i5.4$) are particularly emphasized, as they enable synchronization and active involvement of all participants across manufacturing, logistics, and assembly operations. This integration helps prevent the production of defective elements and improves manufacturing rates [39]. The emergence of these variables reflects a transition from project-based logic to system-oriented production management, which is essential for achieving scalability, repeatability, and efficiency in the industrialized construction sector.

Second, variables related to capacities (MLa_v2), management practices (MLa_v3), and management capabilities (MLa_v4) emerge as enabling dimensions that support the operationalization of MLa processes. The literature consistently highlights that achieving higher maturity levels requires not only structured processes but also organizational readiness in terms of resources, skills, and coordination mechanisms [25,45]. Within this group, indicators such as supply chain reliability (MLa_i2.3), flexible team capacity (MLa_i2.5), planning system implementation (MLa_i4.3), Capability to manage off-site and on-site production synchronization (MLa_i4.4), and just-in-time logistics (MLa_i3.11) are dominant due to their central role in ensuring workflow continuity and minimizing disruptions. This aligns with prior research identifying fragmentation and lack of coordination among stakeholders as major barriers to OSC adoption, particularly in emerging economies [19,20,24].

Finally, variables such as sustainable MLa approaches (MLa_v6) and CITs applications (MLa_v6) emerge as advanced maturity dimensions. Their comparatively lower citation frequency does not imply reduced importance but rather indicates that their adoption is typically contingent upon the prior establishment of stable processes and organizational capabilities. Technologies such as BIM, RFID, and IoT-enabled systems (MLa_i7.1, MLa_i7.2) function as performance enhancers by improving traceability, visibility, and coordination across the supply chain [84,101], but their effectiveness depends on structured workflows and reliable data environments.

Similarly, sustainability-related indicators (e.g., efficient resource utilization, MLa_i6.1) are often derived from improvements in production efficiency, as waste reduction and process optimization naturally lead to better environmental performance [45,86]. This explains their lower dominance in early maturity stages, particularly in emerging economies, where companies prioritize operational stability and cost efficiency before investing in advanced technological and sustainability-driven strategies.

Overall, the literature suggests that the identified variables reflect a progressive maturity pathway, in which organizations evolve from establishing production stability (MLa_v1, MLa_v5) to developing enabling capabilities (MLa_v2–MLa_v4) and ultimately to integrating advanced technologies and sustainability practices (MLa_v6–MLa_v7). This layered interpretation provides a coherent explanation for both the emergence of the variables and the relative dominance of specific indicators within each dimension.

3.1.2. Analyzing the Structure of the Preliminary Evaluation System

- *Collaborative meetings: structuring the preliminary evaluation system*

Additionally, Table 2 presents the indicators identified through the triangulation process. The collaborative meetings were the first instance in the triangulation process. They guided the authors in making adjustments to the OSC-MLa MM evaluation system's structure regarding the description and order of the variables and indicators that comprise it. For example, the first variable (MLa_v1) was described as an activity that should be performed, rather than one that should be performed and managed. Therefore, the term "management" was added to its description.

Furthermore, the experts suggested incorporating logistics indicators into the variable composition and description, rather than treating them as separate variables, since logistics is an inherent aspect of manufacturing and assembly operations and of their interactions. Additionally, the experts gave suggestions about the instrument. They were mostly focused on the proper selection of respondents and the strategic concepts to be included to clarify the questionnaire-answering process. Regarding respondents' profiles, the experts recommended an integrated view of manufacturing, logistics, and assembly operations that extends beyond their specialized work areas. Besides that, the experts indicated that a precise concept should be included for the 5S approach, workplace configuration,

manufacturing layout, temporary/mobile factory, visual management, last planner system (LPs), and Just-in-Time (JIT), among other concepts and terminologies defined in the variables.

- *Questionnaire survey: measuring the agreement level of MLa variables & indicators*

The main outcome of the questionnaire survey was the inclusion of 5 new indicators, bringing the total to 56. These indicators are related to MLa_v3, MLa_v6, and MLa_v7. Most indicators were at a threshold between 4 and 4.8 in the agreement average rate. The highest average agreement level was obtained by the indicator “Frequent productivity tracking and management for manufacturing and assembly operations (MLa_i 3.3)”. There were a few exceptions. For instance, indicators “Temporary/mobile factory deployed on-site as needed (MLa_i 2.7)”, “Tracing and tracking materials/equipment in real-time, supported by CITs (e.g., RFID, GPS, Bluetooth-based sensors) along the supply chain from production plants to the site (MLa_i 7.1),” and “CITs oriented to control safety issues and risks (e.g., use of physiological sensors and RFID to monitor workers and works condition, respectively) in advance (MLa_i 7.10)” reached an average agreement of 2.9 (intermediate agreement), and 3.4 (threshold intermediate and high agreement) for the last two indicators. These indicators were further assessed in the subsequent triangulation stage through semi-structured interviews to better understand the reasons for their agreement value and to evaluate their pertinence within the model.

- *Semi-structured interviews: experts’ deep dive*

The semi-structured interviews helped deepen understanding of the practical implications of the questionnaire survey results. They added another instance of receiving feedback about the model structure. For instance, regarding the indicator that received the lowest score (temporary/mobile factory deployed on-site as needed, MLa_i 2.7), the experts said that this indicator can be adopted in specific cases, such as when site access is difficult, and the building comprises simple elements. Besides that, it would depend on each company’s OSC business orientation. Other arguments were oriented to concept basis; for example, one expert mentioned that “the OSC objective is to manufacture the building parts in a controlled environment to reach high-quality standards, and this can only be achieved in a permanent factory, and that it would be difficult to achieve in a temporary/mobile factory.” Comments favoring indicator MLa_i 2.7 noted that offering this manufacturing flexibility adds value and enhances the OSC business’s competitiveness compared to traditional methods.

For the other two indicators, the experts mentioned similar arguments. In the first case (MLa_i 7.1), they said that although CITs are fundamental to supporting the tracing and tracking of modules/elements, their full adoption depends on other factors, such as the company’s production level and the necessity of incorporating technology into the manufacturing process. For the second case (MLa_i 7.10), the experts noted that CITs support for safety management is not mandatory in most cases (e.g., monitoring oxygen levels in confined spaces would be an exception). Overall, the experts agreed to retain these indicators in the model, as the semi-structured interviews confirmed that their lower agreement levels were mainly associated with context-specific applicability rather than a lack of relevance.

Finally, the experts offered general suggestions on the order and structure. For instance, they recommended that the MLa_i1.6, which is oriented to “worker safety at workplaces” and originally belonged to MLa_v6, be extracted from this variable and included in MLa_v1 because they considered it more related to “Workplace operations configuration” than to a sustainable-social aspect.

3.2. Weight Estimation of the Maturity Evaluation System

As an initial assessment of the AHP weighting results, the consistency of both the individual and consolidated expert judgments was examined. The individual pairwise comparison matrices produced consistency ratios of 0.092, 0.096, 0.076, 0.017, and 0.073 for the five experts, respectively. The consolidated matrix yielded a consistency ratio of 0.021. All individual and consolidated values were below the adopted threshold of 0.10, indicating an acceptable level of consistency in the judgments (Appendix A—Tables A1 and A2).

Before interpreting the AHP results, it is important to clarify how potentially overlapping relationships among the evaluation criteria were addressed. Although some variables and indicators are conceptually interrelated, their boundaries were defined according to their primary evaluative purpose. Indicators that could potentially relate to more than one variable were assigned only once, based on the dimension they predominantly represented, thereby reducing redundancy and avoiding double counting. For example, capacities refer to the resources and conditions available to support MLa operations, management practices concern the activities regularly implemented, management capabilities represent the organizational ability to execute and sustain those practices, and process orientation reflects how these activities are integrated across the production system. During the pairwise comparisons, the experts evaluated each variable based on its complete definition and associated set of indicators rather than on its title alone. Thus, the evaluation acknowledged the interdependence among the criteria while maintaining sufficiently distinct analytical boundaries for the AHP assessment.

Figure 4 shows the results of the AHP. The pairwise comparison conducted by the expert panel revealed a three-level hierarchy within the OSC-MLa maturity evaluation system. At the first level, MLa_v1 and MLa_v5 had the highest weights, accounting for 25.00% and 21.10% of the total phase weight, respectively. This result is consistent with the layered configuration identified in the literature review outcomes, in which both variables emerged as foundational dimensions of maturity. In particular, workplace configuration management (MLa_v1) underscores the importance of establishing organized, standardized, and reliable production conditions (e.g., by applying the 5S approach) as a basis for productivity evolution and effective MLa operations [35,37,106]. In parallel, the high weighting assigned to MLa_v5 reinforces the importance of adopting OSC as a process-oriented and strategically integrated approach to project delivery, rather than as an isolated construction method [28]. Strong orientation of OSC companies to improve process efficiency led to reduced cost waste [106] and made OSC more attractive to non-adopters [39]. From this perspective, the prominence of both variables indicates that the experts considered the stabilization of workplace conditions and the consolidation of a process-oriented logic as the primary basis for increasing MLa maturity. This hierarchy also indicates that the incorporation of Lean Construction within the model is not limited to isolated tools, but is reflected in the prioritization of variables MLa_v1 and MLa_v5, which are core principles of Lean Production.

The second level comprised MLa_v4, MLa_v3, and MLa_v2, which obtained 14.30%, 14.20%, and 13.10% of the total phase weight, respectively. These results also align with the interpretation developed in the literature review, where these variables were identified as enabling dimensions that support the operationalization of MLa processes. The relatively similar weights assigned to these variables suggest that the experts viewed them as interdependent elements that must develop in a coordinated manner. The experts mentioned that the capacities in terms of business scope, machinery, support company system (R/t MLa_v2), the implementation of management practices (R/t MLa_v3), and capabilities to apply them properly (R/t MLa_v4) should be aligned to ensure the proper functioning of MLa processes. In this sense, the results indicate that the availability of facilities or resources alone is insuf-

ficient to guarantee effective OSC implementation unless adequate management practices and organizational capabilities support these.

Phase	Variable	Indicator
	<i>Wi = Variable weight</i> $\lambda_{max} = 7.169$ <i>C.R. = 2.1 %</i>	<i>Iw = Indicator weight</i>
Manufacturing, Logistic and assembly phase	MLa _v - 1	25.00%
	MLa _v - 2	13.10%
	MLa _v - 3	14.20%
	MLa _v - 4	14.30%
	MLa _v - 5	21.10%
	MLa _v - 6	4.70%
	MLa _v - 7	7.50%
		· Six (6) Indicators · <i>Iw</i>: 16.67 % per indicator · Seven (7) Indicators · <i>Iw</i>: 14.28 % per indicator · Thirteen (13) Indicators · <i>Iw</i>: 17.69 % per indicator · Seven (7) Indicators · <i>Iw</i>: 14.28 % per indicator · Nine (9) Indicators · <i>Iw</i>: 11.11 % per indicator · Four (4) Indicators · <i>Iw</i>: 25.00 % per indicator · Ten (10) Indicators · <i>Iw</i>: 10.00 % per indicator

Figure 4. Weights Estimation of the OSC-MLa MM.

Finally, the third hierarchical level included MLa_v7 and MLa_v6, with weights of 7.50% and 4.70%, respectively. These results suggest that the experts viewed CITs applications and sustainability-oriented approaches as dimensions that typically become more relevant at more mature stages of OSC adoption, once operational stability, process integration, and organizational capabilities have already been established. This is consistent with the LR outcomes, in which both variables are associated with performance enhancement rather than with the initial structuring of MLa operations.

3.3. Maturity Levels and Conceptualizations of Variables

Table A3 (Appendix A) shows the conceptualization of maturity levels for each MLa variable (*Va*). The conceptualization of maturity levels is a central component of the OSC-MLa maturity model, as it provides a structured framework for interpreting how organizations evolve in their adoption of manufacturing, logistics, and assembly practices. The table is structured as a variable-by-level matrix, where each row corresponds to a specific MLa variable and each column represents a maturity level. Within each cell, qualitative descriptors define the conceptualization (e.g., practices, behaviors, and organizational conditions) associated with that level of maturity.

The experts agreed to define three progressive levels of maturity for each variable that comprises the model. The terminology of each level is: 1. Initial, 2. Improved, and 3. Optimized. Level 1 indicates organizations characterized by manual and ad hoc practices, a high reliance on individual expertise, and limited integration across manufacturing, logistics, and assembly operations. The improved level (level 2) reflects a transitional stage in which structured practices, basic formal procedures, and selective technological or semi-automated support begin to guide operations. Organizations at this level generally achieve acceptable coordination and control; however, implementation is not yet fully consistent, integrated, or systematically embedded across the production system, and important decisions still rely to some extent on human intervention and experiential knowledge. At Level 3, which represents a high level of maturity, companies usually achieve high levels of automation and standardization in their MLa processes, and they have been developing detailed, formal procedures to support the requirements for an effective MLa practice and process adoption.

The maturity-level conceptualization also reflects the progressive incorporation of lean-oriented practices and related cultural conditions across OSC-MLa operations. As organizations move from lower to higher maturity levels, they evolve from reactive and weakly standardized practices toward more structured conditions supported by 5S-based workplace organization, visual management, planning-system discipline, just-in-time coordination, waste and variability reduction, and continuous improvement. At the same time, the model captures a cultural shift toward greater worker involvement, shared operational awareness, and stronger process discipline, which are essential for sustaining reliable MLa performance.

These levels reflect an evolutionary pathway from fragmented and reactive practices toward integrated, standardized, and continuously improving production systems. This allows the model to capture not only what practices are adopted, but also how effectively they are embedded within the production system. As such, the table serves as both a diagnostic tool for assessing current maturity levels and a prescriptive guide for identifying pathways to higher performance in OSC-MLa operations.

3.4. Feasibility Assessment of the OSC-MLa MM: A Case Study

3.4.1. Characteristics and Selection of the Case Study

A case study was conducted to explore the feasibility of applying the OSC-MLa maturity model in a real organizational context. An Off-site Chilean company was assessed by applying the model. At the end of the assessment, company professionals provided feedback on the model's perceived applicability and practical usefulness. The characteristics of the case study were defined according to the methodology selection criteria established in this study. The company is a recognized player in Chile's construction sector, focused on industrial housing. It is a gold member of the Industrialized Construction Council of Chile (CCI) and a pioneer in steel construction. The company uses semi-automatic machinery to support part of the manufacturing process of components and elements that are pre-assembled off-site and finally erected in situ. This company has been in the market for ten years. Currently, it has a production rate of 79,200 m² of construction per year in the housing market.

3.4.2. Data Collection: OSC-MLa Maturity Assessment and Preliminary Applicability Evaluation

The maturity assessment was conducted through two (2) semi-structured interviews totaling ninety minutes and a plant visit by the authors. The visit to the plant included touring the assembly lines to better understand and verify the MLa process. It ended with a face-to-face collaborative meeting at the company's facilities. The preliminary model applicability evaluation was conducted through an online collaborative meeting lasting 90 min. In this case study, three company professionals were involved. Two of them are middle managers, and one is the Chief of the production plant. The middle managers and the factory Chief have ten years and 18 years of experience in the AEC industry, respectively. Also, all the professionals are civil engineers and have postgraduate studies in construction management (i.e., Magister in Sciences).

3.4.3. Overall Description of the OSC-MLa Maturity Assessment

The company reached an overall maturity phase score (MLa Os) of 1.58 (Figure 5). Following established sensitivity-analysis approaches for deterministic multi-criteria models [73], a one-at-a-time analysis was conducted to examine whether the case-study diagnosis was materially influenced by the equal allocation of local weights among the indicators. The weight of each of the 56 indicators was independently increased and decreased by 20%, while the remaining weights within the corresponding variable were

proportionally normalized to preserve a total local weight of 100%. Across the 112 resulting scenarios, the overall maturity score ranged from 1.58 to 1.59, compared with the baseline value of 1.58. The maximum absolute deviation was 0.006 points, equivalent to approximately 0.36% of the baseline score. The overall maturity interpretation and the relative performance pattern of the variables remained stable. These results indicate that the case-study diagnosis was not materially sensitive to moderate variations in individual indicator weights.

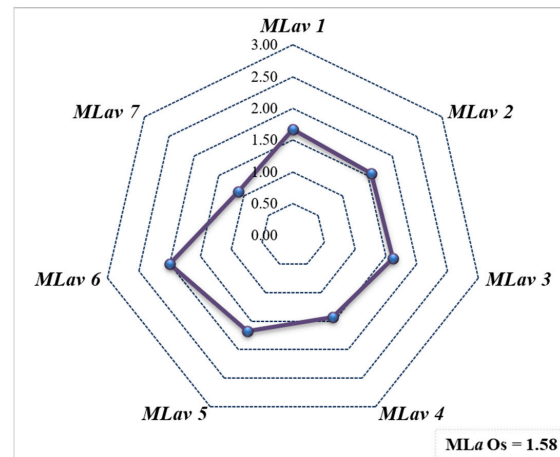


Figure 5. OSC-MLa maturity assessment.

Regarding the variable-level results, MLa_v6 (Sustainable manufacturing, logistics, and assembly approach) obtained the highest score (2.00). This result is supported by concrete sustainability-oriented practices within the company's operations, including the use of solar panels, regular training workshops, the incorporation of materials with improved environmental performance, such as cyclopentane for thermal insulation, and environmental management certification under ISO 14001:2015 [107]. These actions suggest that sustainability is addressed through both operational measures and formal management commitments, which helps explain the comparatively high score achieved in this variable. The next-highest scores were obtained by MLa_v1 (Manufacture and assembly workplace configuration management for optimization, flexibility, and standardized workflow) and MLa_v5 (Manufacturing, logistics, and assembly as a process-oriented approach), both with a score of 1.67.

Regarding MLa_v1 , the company has a periodic routine to organize workplaces (manufacturing and assembly sites) and ensure the proper and safe use of the factory space. In addition, the company can adapt to internal logistics changes. However, because the company is growing (e.g., high project demand and factory expansion), it has some limitations in terms of workers who support the adaptation of logistics plans to changes in workplace configuration (R/t $MLa_i1.2$). The professionals mentioned that the company frequently implements improvements to MA operations (e.g., process standardization). However, those improvements have only been discussed among middle management. Nevertheless, the company offers positive incentives to encourage operators to participate in the process optimization. Currently, they are struggling to balance crews' activities and workflows. The professionals attributed this issue to the lack of a formal strategy for the expansion process.

Regarding MLa_v5 , the professionals indicated that the company has established an industrialization department and increasingly approaches OSC as a strategic business model, in which stakeholder alignment is required to support project delivery (R/t $MLa_i5.1$). However, this condition remains partial, as key supply chain actors, particularly logistics providers, have not yet been fully integrated into the development of systemic construction

solutions. The company has also developed standard technical solutions with detailed manufacturing and assembly specifications, which support defect management and facilitate quality inspection procedures (R/t MLa_i5.7). Nevertheless, these activities are still mainly managed at the tactical level by middle management, with limited operator involvement, which reduces responsiveness and constrains the timely resolution of production defects. In this context, quality leaders play an important role in monitoring production (R/t MLa_i5.8), although this function has not yet evolved into a more distributed quality-control routine across operational levels.

In third place, MLa_v3 (management practices for reliable and optimized manufacturing, logistics, and assembly processes) obtained a score of 1.62. This result reflects a context in which several management practices are already present, but their implementation remains partial and uneven across organizational levels. For example, the company routinely tracks productivity through basic performance indicators, such as pounds of steel used and the types of elements produced (e.g., trusses, panels, and roofs) (R/t MLa_i3.3). However, these metrics provide only a broad view of performance, which limits their usefulness for detailed operational control. Moreover, their implementation depends largely on middle management initiative, and the results are mainly discussed at the top-management level. In addition, visual management practices are not systematically used, and performance information is not shared with operators, which limits broader production awareness and constrains operational-level feedback (R/t MLa_i3.1). A similar intermediate condition was observed in relation to logistics planning. The company shows a clear intention to align off-site production with on-site execution requirements (R/t MLa_i3.11), as reflected in the limited storage time of pre-assembly elements at the factory. However, insufficient coordination with subcontractors means that transportation constraints and the flow of in situ activities are not fully considered, potentially compromising component integrity and creating bottlenecks at the job site, with materials waiting to be assembled.

Variables MLa_v2 and MLa_v4 obtained scores of 1.57 and 1.43, respectively. In the case of MLa_v2, the score reflects the presence of some enabling capacities, although these remain only partially developed. For example, the professionals indicated that the company maintains reliable supply relationships to some extent, which contributes to the continuity of manufacturing and assembly operations (R/t MLa_i2.3). However, many strategic suppliers and contractors are not yet linked by stable commercial agreements, suggesting considerable room for improvement in developing long-term relationships with key stakeholders. Similarly, although some machines can perform different tasks, most are still designed for specific functions, and even where flexibility is technically possible, it is only marginally used, with most equipment continuing to support a single activity. In addition, adjustments still require manual intervention (R/t MLa_i2.1). A comparable intermediate condition was observed regarding workforce flexibility. During the visit, the authors verified that workers were capable of performing various tasks involved in the manufacturing process (R/t MLa_i2.6); however, they lacked sufficient autonomy to resolve problems that arose during production. On several occasions, workers had to stop their activities to consult middle management and wait for authorization before resuming work, which limited operational responsiveness.

For MLa_v4, the lower score reflects more evident weaknesses in planning and synchronization capabilities. In relation to planning practices (R/t MLa_i4.3), the company seeks to minimize work in progress; however, middle management indicated that the current monthly reporting cycle should be shorter and that crew leaders are not regularly involved in the planning process. In addition, limitations were identified in the management of production and supply chain issues (R/t MLa_i4.4). For example, storage times for some materials were not being met, while others had to be returned from the job site. The

professionals explained that, in response to these issues, the company has gradually had to set up additional storage spaces in the plant, suggesting difficulties in anticipating and managing disruptions affecting production and supply chain flows. Overall, these findings indicate that, although some relevant capacities are present, both variables still exhibit important gaps that constrain the reliability and coordination of MLa operations.

Finally, MLa_v7 obtained the lowest score (1.10). Although the company has attempted to incorporate technologies to support manufacturing and assembly operations, the assessment revealed a substantial improvement gap. RFID is used to track materials from the production plant to the site (R/t MLa_i7.1); however, this application is not integrated with other stakeholders (e.g., MEP disciplines) and remains largely isolated, as it is not connected to cloud-based systems. Likewise, the company does not use dedicated logistics software to model alternative scenarios, instead, it relies on basic tools such as Excel spreadsheets that offer limited automation for logistics analysis. In relation to auxiliary technologies for site management (R/t MLa_i7.9), some in situ applications have begun to be tested, including RFID-based monitoring of component assembly sequences. However, these applications remain at an incipient stage, and there is not yet sufficient evidence of their effective use in supporting site operations.

3.4.4. Preliminary Model Applicability Assessment Outcomes

The case study provided preliminary evidence regarding the model's feasibility and applicability in a real organizational context. This assessment was conducted after the detailed evaluation of the company's manufacturing, logistics, and assembly operations. The preliminary applicability assessment followed the seven criteria established in the research methodology section. Most criteria were rated at a high level of achievement; only criteria 1 and 2 have been rated at a moderate level of achievement. Table 3 presents the outcomes of the preliminary model assessment.

Table 3. Criteria and Outcomes of the Preliminary Model Applicability Assessment.

ID	Criteria (C _r)	Level of Achievement				
		1	2	3	4	5
C _r 1	Information quality of the OSC-design MM					
C _r 2	Completeness of the model information					
C _r 3	Accuracy of the weight for each variable					
C _r 4	Model predictability to deliver accurate diagnostic					
C _r 5	Clarity of maturity level descriptions					
C _r 6	Implementation process practicability					
C _r 7	Usefulness of the model assessment					

4. Discussion

After describing the results of each methodological step, this section discusses the findings from two fundamental perspectives: (i) the qualitative interpretation of the expert reasoning underlying the AHP-derived variable weights and the resulting maturity hierarchy, and (ii) the preliminary assessment of the model's applicability. The following subsection synthesizes the expert judgments that explain the relative positioning and interrelationships of the foundational, enabling, and advanced maturity dimensions.

4.1. Overall Maturity Analysis: Variables Weighting Criteria

The prominence of workplace configuration management (MLa_v1) reflects its foundational role in establishing stable and reliable conditions for manufacturing, logistics, and assembly operations. According to the experts, organized workplaces, appropriate material and tool locations, standardized workflows, and safe operating conditions (e.g., MLa_i1.1, MLa_i1.3, and MLa_i1.6) reduce operational errors and quality deficiencies while providing

the basis for developing more advanced capacities, practices, and management capabilities. From this perspective, the capacities represented by MLa_v2 , such as manufacturing flexibility, reconfigurable layouts, and efficient internal logistics, cannot be fully exploited without an orderly and controlled workplace. Similarly, the management practices included in MLa_v3 , such as reducing workflow disruptions (e.g., $MLa_i3.4$) and preparing just-in-time logistics plans (e.g., $MLa_i3.11$), depend on stable workplace conditions that support continuity, inventory organization, and production reliability. The same logic applies to MLa_v4 : an experienced team capable of supporting OSC business development (e.g., $MLa_i4.1$), together with adaptable workers, remains essential, but their capabilities are more effectively mobilized when production and assembly activities are supported by clear workplace arrangements and standardized operating conditions. The experts illustrated this relationship through situations in which language barriers make the communication of instructions and technical specifications more difficult. Although such barriers do not necessarily prevent work from continuing, they can increase reliance on workers' experience and on learning through trial and error. Appropriate workplace configuration and standardized routines can reduce the variability and risk associated with this informal adaptation. These relationships explain why MLa_v1 received greater weight than MLa_v2 , MLa_v3 , and MLa_v4 .

The comparison between MLa_v1 and process orientation (MLa_v5) provides a more nuanced interpretation because both variables constitute the principal foundations of the maturity structure. MLa_v1 enables companies to understand and stabilize what occurs within the factory and across downstream logistics and assembly operations. MLa_v5 , in turn, ensures that these conditions are translated into formalized, coordinated, and systematically managed processes. The experts therefore viewed the two variables as complementary and expected them to evolve in parallel. Workplace configuration provides the physical and operational conditions for effective MLa performance, whereas process orientation connects these conditions to organizational objectives and structured routines. For example, reducing waste and variability (e.g., $MLa_i5.6$) requires both knowledge of workplace operations and a systematic approach to coordinating production flows (R/t MLa_v1). This interpretation is consistent with Lean Construction principles, particularly the emphasis on workflow reliability, standardization, waste reduction, and continuous improvement. The slightly higher weighting of MLa_v1 suggests that operational stability was perceived as an initial requirement, but not as a substitute for the process-oriented logic represented by MLa_v5 .

The comparisons involving sustainability (MLa_v6) and CITs applications (MLa_v7) further distinguish foundational from advanced maturity dimensions. The experts considered workplace safety within MLa_v1 to be a basic operational and legal requirement that should be addressed before pursuing broader sustainability objectives. They emphasized that production efficiency cannot be regarded as an improvement if it is achieved through a workplace configuration that exposes plant operators to unacceptable risks. They also noted that environmental benefits frequently emerge from improvements initially motivated by operational efficiency. For example, optimizing transportation routes or machinery use may reduce fuel consumption, pressure on the transportation infrastructure, operating hours, costs, and emissions simultaneously. As companies mature, however, environmental performance may become a more explicit decision criterion, particularly when financial incentives or regulatory penalties related to CO₂ emissions encourage the evaluation of machinery and processes in terms of both productivity and energy efficiency. Conducting such comprehensive assessments, including evaluations of energy consumption, carbon emissions, and waste-to-resource strategies, generally requires greater organizational maturity, specialized knowledge, and technological support. Sustainability was therefore interpreted as an advanced dimension whose systematic implementation depends on the prior consolidation of operational and managerial conditions.

A similar interpretation emerged for CITs applications. Technologies such as GPS, RFID, and BIM can substantially enhance component tracking, logistics coordination, interference detection, quality control, and progress monitoring. Nevertheless, the experts emphasized that these technologies are not normally the starting point of maturity development. Companies can still perform essential activities manually, such as interpret production information, quality control, although with lower efficiency, whereas the absence of organized workplaces, clear procedures, and competent personnel can prevent technologies from producing consistent benefits. CITs was therefore regarded as an advanced performance enabler rather than an initial condition for effective MLa operations. This reasoning explains why MLa_v1, MLa_v4, and MLa_v5 received greater importance than MLa_v7. In particular, process orientation was considered necessary to ensure that CITs is embedded within clear procedures and systematic workflows rather than introduced as an isolated technological solution.

The relationships between MLa_v2, MLa_v3, and MLa_v4 clarify the role of the enabling dimensions. MLa_v2 represents the resources and operational conditions available to support MLa, manufacturing flexibility, reconfigurable layouts, and efficient internal logistics arrangements (e.g., MLa_i2.1, MLa_i2.2, and MLa_i2.5), as well as workforce adaptability and temporary or mobile-factory capacity (e.g., MLa_i2.6 and MLa_i2.7). However, some of these capacities may be difficult to establish, particularly in emerging OSC contexts. The experts highlighted constraints associated with multifunctional workers, temporary or mobile factories, employee resistance, contractual conditions, and high workforce turnover. Consequently, management practices under MLa_v3 were perceived as more immediately applicable for strengthening reliable OSC adoption. At the same time, MLa_v3 and MLa_v4 were considered closely interrelated. Management practices provide repeated organizational routines through which capabilities can be developed, while management capabilities determine whether those practices can be executed and sustained effectively. For example, just-in-time logistics planning requires both appropriate personnel capabilities (MLa_i4.3 and MLa_i4.4) and collaborative planning practices supported by concurrent engineering (MLa_i3.13). Similarly, the repeated application of supply-chain codes and standards (MLa_i3.7) can progressively support the development of an integrated product quality-control capability (MLa_i4.6). The similar weights assigned to MLa_v3 and MLa_v4 therefore reflect their reciprocal and parallel development.

Process orientation (MLa_v5) connects these enabling dimensions by formalizing how resources, practices, and capabilities are coordinated. The experts emphasized that capacities and individual expertise are insufficient when they are not supported by structured procedures. When a defect is identified during manufacturing, for example, formalized processes enable its timely detection, define the appropriate response, and allow workers' expertise to be applied consistently. Likewise, management practices generate more reliable outcomes when they form part of an integrated process rather than being implemented as isolated actions. This explains why MLa_v5 received greater weight than MLa_v2, MLa_v3, and MLa_v4 and reinforces its cross-cutting role across the OSC project-delivery system.

Overall, the weighted hierarchy suggests that OSC-MLa maturity develops through three interconnected layers. The foundational layer comprises workplace configuration and process orientation, which establish operational stability and systematic management. The enabling layer comprises capacities, management practices, and management capabilities, which operationalize and sustain MLa processes. Sustainability and CITs applications constitute the advanced layer, enhancing organizational performance once the preceding conditions have been consolidated. This hierarchy does not imply that the variables develop independently or in a strictly linear sequence. Rather, it indicates differences in their relative foundational importance and the conditions under which they can generate value. The

findings therefore reinforce the treatment of manufacturing, logistics, and assembly as a single interdependent operational phase: capacities and decisions developed in one domain affect workflow reliability, coordination, and performance in the others. They also show that Lean Construction principles are reflected not only through specific practices but through the prioritization of workplace stability, process orientation, coordination, and progressive capability development across the maturity structure.

4.2. Model Applicability Assessment

Regarding the quality of the information (C_r1), the professionals indicated that the model covers the fundamental MLa variables that an OSC company should consider for successful project delivery. The information regarding variables and indicators was perceived as consistent, easy to understand, and presented in a logical order. In addition, the information aligns with international industry recommendations (e.g., 2021 ICC/MBI 1200) and the adoption of proven successful management practices (e.g., LC practices). About the completeness of the information (C_r2), the professionals added that the model covers a systemic view of the approach to MLa operations. An example is the conjunction that addresses MLa_v2 , MLa_v3 , and MLa_v4 variables, which support the operationalization of MLa processes. Sometimes, companies focus on increasing their capacities ($R/t\ MLa_v2$) in terms of machinery and equipment and neglect to strengthen management practices ($R/t\ MLa_v3$) and capabilities to manage (MLa_v4) MLa . The experts noted that to address this issue, the model integrates these visions into a single structure, evaluates them, describes their appropriate adoption, and assigns weights to them. From their perspective, this structure supports companies in allocating economic and human resources more effectively to improve the maturity of MLa operations.

In this regard, the professionals pointed out that the model highlighted fundamental aspects that are not often developed with a clear strategy, but instead tend to evolve organically as organizational capacities. A representative example is indicator $MLa_i2.3$ within the variable MLa_v2 , which refers to the capability to establish reliable supply relationships while ensuring workflow continuity. The professionals emphasized that this should be treated as a capability to be intentionally developed. Establishing such stability contributes not only to workflow continuity but also to the standardization and improvement of the elements and modules that compose the building. It strengthens trust and commitment among actors and motivates the development of materials and products through in-depth incursions. However, the current scenario is that most OSC companies do not see it as a capability to be developed, but rather as a relationship that is strengthened through increasing interactions between stakeholders and that depends heavily on individuals' soft skills.

Regarding the weight of variables (C_r3), the professionals indicated a high level of achievement. They mentioned that the weighting for each variable adequately expressed the "from," i.e., the base variables that should be adopted initially (foundational production dimensions, MLa_v1 and MLa_v5), the variables that should be applied for reliable operationalization of MLa process (MLa_v2 , MLa_v3 , and MLa_v4), and those variables that allow for improving the productivity of the business strategy (MLa_v6 and MLa_v7). Regarding the model's predictability (C_r4) and the clarity of its maturity-level descriptions (C_r5), the professionals indicated that the model provided a score and description that were closely aligned with company's current state. They expressed satisfaction with the descriptions of each maturity level and considered this one of the most challenging aspects of model development. From the practitioners' perspective, the scoring was well aligned with their experience. For instance, the maturity-level description and score regarding the "visual management practice" ($R/t\ MLa_i3.1$) closely reflected the company's current conditions. Nowadays, manufacturers are looking to generate reliable metrics that are practically

developed and shared, communicated at different levels (top, middle management, and operators), and that support agile decision-making during manufacturing and assembly. They said, “We feel very happy with the diagnosis. It is valuable information that helps us in the expanding process we are currently carrying out.”

The professionals reported that implementing the model was practical (C_r6) in the case-study context and that they did not feel evaluated. On the contrary, the implementation served as a learning instance, allowing them to better understand the importance of strengthening foundational dimensions such as MLa_v1 and MLa_v5 , which are central to the stability and systematic management of MLa operations. For example, the professionals recognized opportunities to reinforce workplace organization through clearer visual controls and more structured 5S practices ($R/t\ MLa_i1.1$), and to improve workplace layout to better support fabrication and assembly activities while strengthening workers’ safety ($R/t\ MLa_i1.5$ and $MLa_i1.6$). They also acknowledged that these improvements should be embedded within a broader process-oriented approach (MLa_v5), rather than treated as isolated operational adjustments. In their view, such changes could help reduce production variability and improve the stability of MLa operations.

Regarding the usefulness of the OSC- MLa MM (C_r7), the professionals indicated that the model constitutes a significant contribution to the industry because it provides greater clarity on the critical aspects that companies must address to improve MLa operations. In particular, they noted that the prominence of process orientation within the model hierarchy ($R/t\ MLa_v5$) highlighted that OSC should be managed through a systematic, coordinated approach rather than through isolated operational decisions. The professionals also highlighted that, in the logistics domain, the company had previously implemented improvements through trial and error, often recognizing their broader effects on production and assembly only after problems had emerged. In this sense, they considered that an earlier maturity assessment might have helped reduce additional costs and working hours devoted to resolving unforeseen events, while directing attention to the relevant aspects identified by the model (e.g., $MLa_i1.2$, $MLa_i2.4$, $MLa_i2.5$, $MLa_i3.9$, and $MLa_i3.11$). Overall, they emphasized that “the model not only provides a diagnosis of current conditions, but also helps identify, with precision, the areas in which improvement efforts should be concentrated.” This feedback provides preliminary evidence of the model’s perceived usefulness within the assessed organizational context.

5. Conclusions

This research developed a comprehensive OSC- MLa maturity model and conducted a preliminary assessment of its applicability to support the structured improvement of manufacturing, logistics, and assembly operations in OSC. The results indicate that the proposed model provides a structured representation of the interdependence among manufacturing, logistics, and assembly by treating them as a single and interrelated operational phase rather than as isolated functions. In this sense, the model contributes to a better understanding of OSC as an integrated production system and provides a structured mechanism for managing its complexity through progressive maturity development.

A central outcome of the study is the identification of a layered maturity structure composed of foundational, enabling, and advanced dimensions. Workplace configuration management (MLa_v1) and process orientation (MLa_v5) emerged as foundational dimensions, as they provide the conditions required to stabilize production and structure MLa operations systematically. Capacities, management practices, and management capabilities (MLa_v2 – MLa_v4) were positioned as enabling dimensions that support the operationalization of MLa processes, while sustainability and CITs applications (MLa_v6 – MLa_v7) were interpreted as advanced maturity dimensions that become more relevant once prior organi-

zational and operational conditions have been established. This structure was supported by the AHP results, while the case study provided preliminary evidence that the model can identify maturity conditions and reveal improvement paths aligned with the practical challenges of OSC implementation.

5.1. Theoretical Contributions

The first significant theoretical contribution of this research is the development of a structured and multidimensional OSC maturity model composed of a set of 7 variables and 56 indicators. These variables integrate: (i) managerial aspects, (ii) OSC capacities, (iii) sustainability-related considerations, and (iv) advanced technological support aligned with MLa development. Second, the maturity model integrates manufacturing, logistics, and assembly as a single analytical phase, thereby addressing a limitation of previous OSC maturity approaches, which have generally examined these dimensions separately or only partially. Third, it provides an explicit maturity structure supported by variable conceptualization and hierarchical weighting, which enhances its potential analytical, diagnostic, and prescriptive value.

Additionally, the study strengthens the process-oriented understanding of OSC by linking the maturity model to a broader operational logic in which flow reliability, coordination, operational control, and progressive capability development are central. In this regard, the model not only organizes critical success factors into a coherent evaluation system, but also contributes to explaining how the interdependence among manufacturing, logistics, and assembly can be understood within a structured maturity-development perspective. Furthermore, the experts' reasoning during the AHP discussion implicitly reinforces, to some extent, the relevance of LC principles and practices in explaining both the prioritization of foundational variables and the progressive adoption of operational variables in manufacturing, logistics, and assembly. This suggests that, although the model is grounded in a comprehensive review of critical MLa factors, it also supports the relevance of LC as a foundation for understanding and facilitating the management of complexity in OSC.

5.2. Practical Contributions

From a practical standpoint, the proposed model offers organizations a structured framework for diagnosing their current maturity and identifying areas for improvement. The case study provided preliminary evidence that the model support practitioners in recognizing weaknesses that are often not addressed strategically, but instead develop informally or reactively over time. In this sense, the model has the potential to help companies move beyond trial-and-error approaches by providing clearer guidance, through both qualitative and quantitative analyses, on which variables should be prioritized and how improvement efforts can be sequenced more effectively.

A particularly relevant practical contribution is that the model supports a more integrated view of OSC operations. By assessing manufacturing, logistics, and assembly jointly, the model helps organizations recognize how weaknesses in one domain affect performance in the others. This is especially valuable in contexts where OSC adoption remains fragmented and companies invest in machinery, technology, or isolated process improvements without adequately strengthening the operational and managerial conditions required to support them. Therefore, the proposed OSC-MLa maturity model offers practitioners a practical tool to support decision-making, prioritize investments, and guide the progressive strengthening of OSC capabilities.

5.3. Limitations

Despite these contributions, the study has some limitations. First, the maturity assessment was conducted through a single case study involving three company professionals. Although the participants occupied relevant managerial and operational positions and the assessment was

complemented by semi-structured interviews, a plant visit, and direct observation of the manufacturing process, the small participant pool limits the diversity of organizational perspectives represented. In addition, the assessment was conducted within a relatively bounded period and therefore provides a cross-sectional diagnosis rather than evidence of maturity evolution over time. Consequently, the empirical findings reflect the specific company context and market conditions, rather than as full empirical validation or broad generalisability of the model.

Second, although the development of the OSC-MLa maturity model in terms of variables, indicators, and maturity-level conceptualization was based on their potential positive impact at a broader level, the hierarchy of variables was established using the Chilean AEC industry as the reference context for an emerging economy, which may limit the direct transferability of the weighting structure to other national settings. Third, although the assessment instrument was developed and applied successfully within the study, it has not yet been released as an open and reusable tool for broader industry use.

5.4. Future Studies

Future research should extend the model's application primarily to other emerging economies, particularly in South America, to compare maturity patterns across countries and refine it under different institutional and seasonal market conditions. Comparative studies could support the calibration of variables and indicators and help identify context-specific and transferable aspects of MLa maturity in OSC.

Further research is also recommended to assess the model across a broader range of OSC companies and project types, thereby strengthening its empirical robustness and practical applicability. Within each case, future assessments should involve a larger and more diverse group of participants representing different hierarchical levels and functional areas. Such broader participation would support the triangulation of perspectives and provide a more comprehensive assessment of organizational maturity. In addition, the development of an open-source and reusable assessment instrument would allow organizations to reassess their maturity over time, benchmark their progress, and support longitudinal analyses of OSC capability development.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Pontificia Universidad Católica de Chile (protocol code 200820005 and 10 December 2020).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study. At the beginning of the questionnaire, a clear statement clarifying the purpose of the questionnaire and the participation in the survey was voluntary. In addition, no personal or identifiable information was collected, and all responses were treated anonymously.

Data Availability Statement: The datasets presented in this article are not readily available because of confidentiality agreements with the company. The dataset is the property of the company involved in the research and cannot be shared without prior authorization.

Conflicts of Interest: Author Francisco Chitty Gozalo was employed by FINFROCK LLC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MM	Maturity model
MLa	Manufacturing, logistics, and assembly
MLa _v	Manufacturing, logistics, and assembly variable
MLa _i	Manufacturing, logistics, and assembly indicator
OSC-MLa MM	Off-site Construction Manufacturing, logistics, and assembly maturity model
Ra	Research algorithm
Ex	Expert
Csf	Critical success factors
CM/CMs	Collaborative meeting/Collaborative meetings

Appendix A

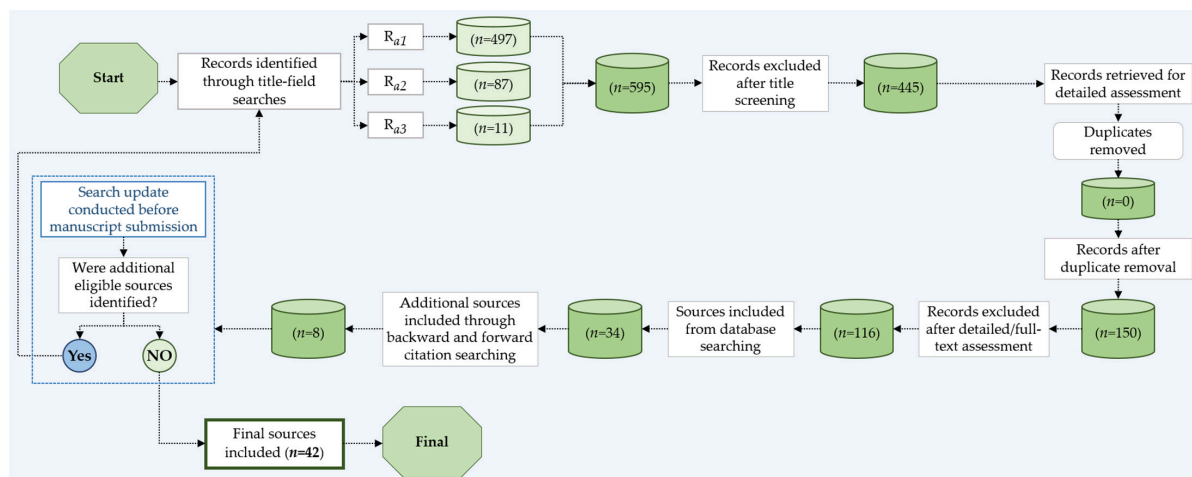


Figure A1. Article protocol selection.

Table A1. Individual Consistency Ratios and Expert Weights.

Expert	Expert Aggregation Weight	C.R
Ex ₆	0.20	0.092
Ex ₇	0.20	0.096
Ex ₈	0.20	0.076
Ex ₉	0.20	0.017
Ex ₁₀	0.20	0.073
Consolidated matrix	-	0.021

Note: Ex = expert; CR = consistency ratio.

Table A2. Consolidated Pairwise Comparison Matrix and Resulting Variable Weights.

Va	MLa _{v1}	MLa _{v2}	MLa _{v3}	MLa _{v4}	MLa _{v5}	MLa _{v6}	MLa _{v7}	Weight	Rank
MLa _{v1}	1.000	1.246	1.380	2.268	1.516	4.360	4.453	0.250	1
MLa _{v2}	0.803	1.000	0.871	0.803	0.644	3.000	1.246	0.131	5
MLa _{v3}	0.725	1.149	1.000	1.000	0.450	2.930	2.237	0.142	4
MLa _{v4}	0.441	1.246	1.000	1.000	0.549	3.680	2.402	0.143	3
MLa _{v5}	0.660	1.552	2.221	1.821	1.000	3.245	2.766	0.211	2
MLa _{v6}	0.229	0.333	0.341	0.272	0.308	1.000	0.450	0.047	7
MLa _{v7}	0.225	0.803	0.447	0.416	0.361	2.221	1.000	0.075	6

Note: The matrix entries represent the element-wise geometric means of the five individual expert judgments. The priority vector was derived using the eigenvector method. The consolidated matrix produced CR = 0.021, below the adopted threshold of 0.10.

Table A3. Conceptualizations of maturity levels for each MLa variable (Va).

Va	Level 1 • Initial	Level 2 • Improved	Level 3 • Optimized
(1)	○ The company rarely has a consistent routine to ensure the organization of “manufacturing and assembly sites,” nor a strategy or method for doing so. The organization of manufacturing and assembly sites highly depends on middle management or operators’ initiative. ○ This often hinders the capacity to develop logistics plans for material flow and storage that adapt to workplace configuration changes. ○ Workplace configurations for defining repetitive tasks are often generated through ad hoc optimizations in manufacturing plants and assembly sites. It depends on each worker’s expertise and initiative. This often leads to variability and desynchronization among activities and workflows in the workplace. Therefore, the workplace layout is usually suboptimal in supporting production and assembly activities. ○ The manufacturing and assembly processes are usually oriented toward workers’ safety to comply with mandatory regulations and to follow basic company protocols.	○ The company periodically has a routine to ensure the organization of “manufacturing and assembly sites”. To this end, there is a strategy or method at the top and middle-management levels, but it is not socialized further with operators. ○ The logistics plans for material flow and storage can be periodically adjusted to accommodate changes in workplace configuration. However, the company sometimes faces difficulties adapting them to evolving production standards and new material requirements (e.g., materials that require stringent storage conditions and/or quality control tests). ○ The definition of repetitive tasks for the workplace configuration is periodically generated to optimize the production system at the factory and site levels. However, the effectiveness of optimization often relies on middle management and worker expertise. This occasionally affects the reliability of the process for balancing and synchronizing crew activities and workflows regarding workplace configuration alternatives. Under these considerations, the company sometimes cannot achieve an optimal workplace configuration due to the lack of a clear strategy or method to be applied. This sometimes creates a gap in workplace layout optimization for supporting manufacturing and assembly operations. ○ Manufacturing and assembly workplace configurations are usually oriented toward workers’ safety and compliance with mandatory regulations. Protocols and procedures are well documented at this level of maturity.	○ The company frequently employs rigorous monitoring to maintain order and ensure the organization at manufacturing and assembly sites. This is usually supported by a strategy or method socialized at the top management level, which is addressed and shared more deeply with middle management and operators. ○ At this level, logistics plans for material flow and storage are always prepared to be aligned and respond quickly to multiple changes in the workplace configuration, including evolving production standards and new material requirements. ○ Workplace configurations for defining repetitive tasks are usually generated by considering system optimization (e.g., from the factory to the site), with a clear method and strategy from top to middle management and workers. This usually allows for a reliable process to balance and synchronize the activities and workflows of the crews regarding alternative workplace configurations. In addition, the company typically provides optimal, efficient workplace layouts to support the development of manufacturing and assembly operations. ○ The manufacturing and assembly workplace configuration is usually rigorously oriented toward workers’ safety. Protocols and procedures are fully developed. At this level, the company usually establishes its own method more rigorously than the industry average to preserve workers’ safety.
(2)	○ The factory is rarely flexible because its machinery is restricted to performing a few different tasks and to adapting sequences. Furthermore, an important part of the production is performed manually. ○ A project-based culture and stakeholder fragmentation characterize the company’s project development. Consequently, there is a poor capacity for reliable supply relationships regarding stable business relationships and compliance with technical standards/supply requirements. Furthermore, project development often suffers from a workflow discontinuity between manufacturing and assembly operations. ○ The project development ecosystem affects the company’s logistics system, which is often fragmented and subject to discontinuity among stakeholders who perform different individual tasks. Consequently, the company often lacks traceability of the production elements/modules. For instance, the precise information of the elements/modules (e.g., location, custodian, and condition) is often limited to the production plants. ○ The fragmentation and the high human dependency (e.g., lack of technological tools) on transmitting (e.g., phone) and collecting data (e.g., papers, manual entry, human measure) impact the inaccuracy (e.g., timely and data inconsistency) to carry out the internal logistics to arrange materials (e.g., inventory management in the manufacturing plants and on-site) and facilities for manufacture and assembly operations. ○ The team supporting the project delivery process often lacks multifunctional workers (e.g., they cannot work across different stations). Some of the workers are usually conservative ones with a change-resistant culture. This contributes to a negative factor that hinders the supply chain’s production flexibility and capacity.	○ The factory often allows some flexibility in its production, with its machinery capable of performing different kinds of tasks, sequences, and working with various materials. Still, it sometimes requires labor in its mechanical system to achieve flexibility. ○ The integration between manufacturers and assemblers often characterizes the company’s project development. This contributes to the company maintaining reliable supply relationships, complying with technical standards, meeting supply requirements, and avoiding production disruptions across manufacturing and assembly operations. ○ Sometimes, logistics system operations that rely on nominated subcontractors or suppliers lack close cooperation or communication, making material/element/module tracing susceptible to inaccuracies. ○ Some specific mechanisms for data collection (e.g., support software) and information-sharing systems are still tied to human faculties (e.g., manual data entry). Despite this, the use of automated tools decreases the margin of error in the data collection process and often has no significant impact on the internal logistics of arranging materials and facilities for manufacturing and assembly operations. ○ The team supporting the project delivery process is often flexible and comprises multifunctional workers (e.g., decentralized responsibility and the ability to work across different stations) who adapt to change when required. However, workers’ autonomy to detect anomalies and solve problems sometimes depends on middle management rather than a formal company strategy that involves them. ○ The organization is occasionally able to set up a temporary/mobile factory on-site for a simpler production process.	○ The factory is usually flexible, as it develops multiple products and quickly switches from one to another. Its machinery and facilities enable it to work with various materials and perform different tasks and sequences without significant labor in its mechanical system. ○ The main stakeholders are usually integrated (e.g., designers, manufacturers, constructors, and strategic suppliers). This project ecosystem enables the company to build strong, reliable supply relationships, ensuring stable business relationships and compliance with technical standards and supply requirements to assure workflow continuity from manufacturing to assembly operations. The company’s logistics system is usually integrated across manufacturing plants and assembly operations, involving all main actors, including strategic suppliers. Therefore, the company can usually trace and monitor the entire production of elements/modules from manufacture to assembly. ○ In addition, the mechanisms for data collecting and information sharing usually require less human intervention (e.g., a high level of autonomy). Low human dependency enables the company to operate internal logistics efficiently and effectively while arranging materials and facilities for manufacturing and assembly. ○ The team that supports the project delivery process is usually flexible; it includes multifunctional workers (e.g., decentralized responsibility, capacity to work across different stations) who share their knowledge and adapt to change when required. A company’s strategy often gives workers autonomy to detect anomalies and solve problems (e.g., to stop production if necessary). ○ The organization is periodically capable of setting down a temporary/mobile factory on-site as needed for the project (e.g., Walnut creek bridge project.)

Table A3. Cont.

Va	Level 1 • Initial	Level 2 • Improved	Level 3 • Optimized
(3)	- The company often lacks visual management adoption to monitor and control manufacturing, logistics, and assembly operations. The measured performance is usually shared and discussed at the top management level and with each stakeholders (e.g., manufacturers, assemblers, strategic suppliers). This lack of transparency and integration limits the generation and frequency of positive feedback among stakeholders on KPI performance and leads to inaccuracies in assessing detailed manufacturing, logistics, and assembly metrics. Consequently, performing detailed metrics (e.g., a value stream map of the manufacturing process) seems impractical, so practices such as predictable task time preparation and frequent productivity tracking and management for MA operations are periodically susceptible to inaccuracy and/or low frequency. - The company's work is sometimes planned based on the company's readiness and urgency assessment, with little consideration for the impact on the project chain. The company sometimes incurs misapplied supply chain codes or standards due to a lack of manufacturing process awareness of their impacts on the OSC strategy for project delivery. - The company's individualism usually affects the implementation of the logistics plan. Information among stakeholders (e.g., manufacturers and assemblers) is regularly delivered untimely, hindering the early assurance of the implementation of project logistics plans (e.g., module/element maneuvering) and leading to an often inaccurate JIT logistics plan for off-site and on-site production. - The company occasionally conducts cross-training programs for employees. The specialized culture prevails, and some workers are resistant to performing other activities.	- The company often employs visual management to monitor and control manufacturing, logistics, and assembly operations. The measured performance is often transparently shared and discussed at the top-middle management level, allowing the company to perform reliable manufacturing and assembly metrics assessments, such as predictable task time preparation and frequent productivity tracking and management for MA operations. However, metrics related to non-internal logistics performance (e.g., accurate measurement of external supply transportation) are sometimes difficult to measure due to a lack of integration with nominated subcontractors or suppliers. Consequently, this sometimes hampers a comprehensive, frequent assessment of productivity, preparation metrics, and their accuracy for MLa. - The company periodically conducts readiness and urgency assessments for production to avoid supply chain disruptions, and it is oriented toward meeting codes and quality standards. Often, this is guaranteed among manufacturers and assemblers. The team members often disseminate and adopt a culture of awareness of manufacturing processes. This often helps to preserve the OSC strategy and contributes to successful project delivery. - The sense of awareness to preserve OSC strategy often encourages manufacturers and assemblers to stay aligned with each other, as well as to provide timely logistics information and early assurance of the project logistics plan's implementation (e.g., module/element maneuvering). However, JIT logistic plan for off-site and on-site production sometimes suffers delays due to not considering restrictions from the rest of the stakeholders (e.g., nominated subcontractors, suppliers). - The company periodically conducts people cross-training programs, only as needed or when the workload is minimal. - The concurrent engineering approach to support MLa is often partially adopted (e.g., when exceptional or emergency events happen, main stakeholders intensify the collaboration and frequency of it)	- The company usually employs visual management to monitor and control manufacturing, logistics, and assembly operations. The performance metrics are usually transparently shared and frequently discussed bidirectionally with top-middle management and operators at the operational level among the main stakeholders during the project delivery process. This allows the company to perform a comprehensive assessment of manufacturing and assembly metrics accurately and frequently, such as predictable task time preparation and frequent productivity tracking and management for MA operations. - The company usually conducts readiness and urgency assessments for production to avoid supply chain disruptions and ensure compliance with codes and quality standards throughout the chain (e.g., involving the main stakeholders), while promoting the team members' awareness of the manufacturing process and preserving the OSC strategy for successful project delivery. - Logistics information among stakeholders (e.g., from manufacturers to builders) is usually delivered accurately and on time, ensuring early assurance of project logistics plan implementation (e.g., module/element maneuvering) and a reliable JIT logistics plan for off-site and on-site production. - The company continuously implements people cross-training programs, increasing flexibility and performance in manufacturing and assembly operations while supporting employees' career development. - The concurrent engineering approach to support MLa is usually fully adopted as part of the company's culture work.
(4)	- The company can often assess the availability and experience of local workers and stakeholders (e.g., designers, manufacturers, and contractors) to support the OSC strategy, but sometimes struggles to obtain forecasts of local labor. Often, the company lacks a structured system for this type of assessment. - The company often employs low-tech mechanisms for data collection (e.g., paper cards, painted labels, and human factors involved in data collection), resulting in difficulties in the retrieval of data for various purposes such as management monitoring, controlling (e.g., measurement and performance analysis), manufacturing, logistics, and assembly operations. - Middle management usually works with traditional planning systems (e.g., push-scheduling-oriented) and struggles to provide timely, accurate plans for manufacturing, logistics, and assembly operations. - The company usually struggles to manage work issues, synchronize operations, and work effectively with off-site and conventional in situ methods. Often, this is due to inadequate adoption of planning systems, a lack of expertise, or a lack of integration among stakeholders. - The company usually cannot establish quality traceability on-site or off-site, and it is not rigorous enough to perform adequate quality controls across manufacturing, logistics, and assembly operations. Some causes are related to a lack of integration and a deep understanding of codes and standards. - The quality company ecosystem is rarely supported by quality leadership that encourages all team members to take responsibility for quality. On the contrary, it depends on the workers' sense of quality. Thus, the company often struggles to meet the minimum quality requirements set by local codes.	- The company can periodically make accurate assessments of the availability and experience of the local workers and stakeholders (e.g., designers, manufacturers, contractors) to support the OSC strategy and acquire forecasts of local labor. At this maturity level, assessments can often be performed by a selected team of experts who select prospective candidates (e.g., from public databases). - The company often employs advanced mechanisms for data collection (e.g., digital tracking and measurement mechanisms for elements) to support various purposes, such as management monitoring and control (e.g., measurement and performance analysis) and manufacturing and assembly operations. Regarding some supportive logistics operations (e.g., external supply transportation), the company sometimes employs inadequate data-collection mechanisms due to poor integration and limited influence over nominated subcontractors and suppliers to implement better mechanisms. - Middle management periodically implements a proper planning system for OSC (e.g., LPS) and regularly provides timely, accurate plans for manufacturing, logistics, and assembly operations. - The company can periodically manage work issues, synchronize operations, and work effectively with off-site and conventional in situ methods. - The company can often establish quality traceability for manufacturing, logistics, and assembly operations, and it complies with codes and standards published by national and international entities to perform adequate quality controls (e.g., conformity with the dimensions and tolerances of the elements). - The initiative of middle management that supports the company's quality leadership; there is often not a top-down quality culture that encourages workers to take responsibility for quality. The involvement of top management or operators is not frequent. Nevertheless, this context often allows the company to meet the quality requirements set by local codes and standards, with repairs completed rapidly and retrofits kept to a minimum.	- The company can usually assess the availability and experience of local workers and stakeholders (e.g., designers, manufacturers, contractors) to support the OSC strategy and acquire local and regional labor forecasts; At this maturity level, the selected team of experts from the organization would usually expand the assessment scope such as reaching out to academic institutions or other technical groups for their expertise that are aligned with the organization necessities. - The company usually employs top-notch mechanisms for data collection (e.g., RFID, GPS, Cloud technologies, and their combination) to support various purposes, such as management monitoring and control (e.g., measurement and performance analysis), manufacturing, logistics, and assembly operations. - Middle management and crew leaders can usually implement a proper planning system for OSC (e.g., LPS) and provide timely, accurate plans for manufacturing, logistics, and assembly operations. - The company can usually manage work issues, synchronize operations, and work effectively with both off-site and conventional in situ methods. The company usually employs effective planning systems and benefits from a high level of expertise and integration among stakeholders. - The company can usually establish and ensure quality traceability for manufacturing, logistics, and assembly operations, while fully complying with codes and standards to perform adequate quality controls (e.g., dimensions and tolerances of the elements). At this level, the company often has more stringent standards than those published by the national and international entities. - The company's effectiveness in performing quality controls usually stems from a production ecosystem, supported by a quality leadership capacity and a top-down culture that encourages workers to take responsibility for quality. It leads the company to meet the quality requirements set by local codes and standards; repairs at this level are minimal or cosmetic, and retrofits are unusual.

Table A3. Cont.

Va	Level 1 • Initial	Level 2 • Improved	Level 3 • Optimized
(5)	- The company usually considers OSC as an isolated approach, without a rigorous analysis of the implications in the overall project process. - Project delivery work is usually organized around a specific project. Process improvement in manufacturing, logistics, and assembly is generally ad hoc and specific to operations, lacking a systematic view. - The company lacks a bidirectional information flow process among stakeholders, often attributed to the fragmented project development ecosystem. - The production process often cannot effectively maintain continuity between off-site and on-site operations. The company is oriented toward finished-product production rather than a lean-process production orientation, frequently hindering the maintenance of continuity between off-site and on-site operations. - The company struggles to achieve a balanced process that detects and minimizes waste and reduces variability for MLa operations. There is no clear method to employ; it highly depends on the initiative and expertise of workers. - The company usually lacks standards for responding to defects. Therefore, quality control routines often suffer from inaccuracies and are less frequent than they should be. - The decision-making process for supply decisions often considers cost variables over other strategic preferences (e.g., code compliance and supplier history).	- The company often employs OSC as a strategic business approach, considering its implications primarily in manufacturing, internal logistics, and the assembly process. - Project delivery work is periodically organized around transversal processes across projects. Process improvement is sometimes carried out for practices that support manufacturing and assembly operations. However, some logistical processes are not regularly improved due to insufficient integration with nominated subcontractors and suppliers that support specific logistics operations (e.g., external supply transportation and raw material shipment to the factory). Therefore, a systematic view is not often fully achieved. - The company periodically conducts a bidirectional information process between manufacturers and assemblers. Other stakeholders (e.g., nominated subcontractors and suppliers) are not often considered in the bidirectional information process. - The production process often maintains functional continuity between off-site and on-site operations, but with a gap in improvement. In some cases, delays occur due to logistical activities or weaknesses in the established production process. - The company periodically achieves an acceptable balance in its processes, detecting and minimizing waste and reducing variability across manufacturing, internal logistics, and assembly operations. They have basic procedures to do so, but still have room for improvement. For instance, sometimes there is still a dependence on workers' encouragement (e.g., middle management) to perform the mentioned actions (e.g., minimize over-processing or under-processing). - The company often has standards to respond to defects, disseminated at the tactical level (middle management), that support quality control routines. This regularly contributes to satisfactory quality performance in manufacturing, internal logistics, and assembly processes. - The decision-making process for supply decisions is often based on strategic preferences (e.g., code compliance, supplier history).	- The company employs OSC as a strategic business approach, considering its implications in all project delivery processes (e.g., manufacturing, logistics, and assembly) involving all main stakeholders. - The work for project delivery is usually organized around transversal processes that have been used and refined from project to project. This process improvement for manufacturing, logistics, and assembly operations is founded on a systematic approach rather than ad hoc individual-task improvement. - A constant bidirectional flow of information among the main stakeholders also supports process improvement. This contributes to the production process, usually effectively maintaining continuity between off-site and on-site operations by keeping the start times of on-site installations close to the finish times of manufacturing. - The company can mostly achieve a continuous, balanced lean process by detecting and eliminating waste and reducing variability across manufacturing, logistics, and assembly operations, while supporting formal procedures and collaborating with the production team (e.g., middle management and operators). - At this level, the company typically has standards for responding to defects, disseminated at the tactical and operational levels, that support accurate quality control routines and ensure efficient and effective manufacturing, logistics, and assembly processes. - The decision-making process for supply decisions is usually based on multiple strategic factors (e.g., code compliance, supplier history, response times).
(6)	- The company often limits its sustainable approach to the minimum regulatory local requirements for project delivery. - The project activities (manufacturing, logistics, and assembly operations) are usually organized to achieve traditional performance (e.g., cost, time, and quality) rather than to achieve efficient resource use, and sustainability is often seen as a constraint to be overcome within project delivery methods. - The social safety requirements are tied to local regulations, and there is often a lack of proactive capacity to address environmental issues.	- The company is usually aware of the importance of sustainable considerations during project delivery. However, it is often a guideline at the top-middle management level rather than a transversal strategy (e.g., including operators). - The sustainable approach is tied to local regulations and top- and middle-management initiatives. Operators rarely participate in sustainable initiatives. In this context, middle management is periodically engaged in using resources efficiently by minimizing waste for manufacturing, internal logistics, and assembly operations. Also, at this level, the company implements initiatives to incorporate more efficient materials during manufacturing and assembly operations. - The social safety requirements are addressed on time and in compliance with local regulations. At this level, the proactive aptitude of top- and middle-level management can be appreciated.	- The company usually has a sustainable, transversal strategy at the top, middle, and operator levels. - The company's sustainable strategy usually guides and ensures the efficient use of resources during project delivery, including the product's transportation (e.g., travel distance and load protection). This strategy often forms part of the principal organizational targets and is more demanding than the local requirements. The activities are usually organized and executed to minimize waste for manufacturing, logistics, and assembly operations (e.g., reducing traditional wet trades such as plastering and masonry). Furthermore, the company is focused on incorporating efficient materials into product development for manufacturing and assembly (e.g., to reduce energy consumption) and on using energy-efficient heavy machinery across their manufacturing, logistics, and assembly stages. - The company fully addresses social safety requirements, complying with local regulations and incorporating more stringent considerations. A proactive aptitude and a high level of involvement with top- and middle-management communities are mandatory for the organization.
(7)	- The company often lacks applications of CITs to support logistics operations. Human dependency still prevails at this level when performing the logistics task. - The low adoption of CITs periodically makes the company more susceptible to delays in information delivery or less efficient in delivering it. - The company sometimes integrates BIM to support logistics operations (e.g., bill of standard materials). It is still principally implemented at the design level. - In manufacturing operations, the company usually employs human resources for data collection and for following production lines. - Assisting manufacturing operations with CITs and employing other auxiliary technologies, such as cameras and drones, to support assembly operations at the site is rarely applied by companies.	- The company often employs CITs, such as RFID, GPS, or Bluetooth, to support internal logistics operations and capture precise, real-time information about manufacturing plants or assembly sites. At this level, the non-internal logistics operations that do not depend on the company are rarely supported by the CITs mentioned. - The application of CITs is not integrated in a consistent manner (e.g., RFID and GPS used to collect information and track product delivery simultaneously) and is underused. Consequently, the information captured by these technologies is sometimes poorly connected and shared among supply chain stakeholders. - The company often has deeper integration with BIM technologies to support logistics (e.g., piece-handling information and erection sequences). - In manufacturing operations, the company often uses CITs, such as RFID, to record information and track production or operator status to support manufacturing management. Nevertheless, these technologies are sometimes limited to specific functions (e.g., RFID data is not often integrated with performance tools to be shared more practically and faster within the team). Auxiliaries' technologies, such as cameras and drones, are periodically used by companies to support site management at this maturity level, but with some restrictions.	- The company usually employs CITs, such as RFID, GPS, and Bluetooth-based sensors, to support logistics operations, capturing precise, real-time information along the project supply chain from manufacturing plants to assembly. - At this level, the company can often combine these CITs with cloud technologies or the Internet of Things (IoT) to improve real-time communication, integration, synchronization, and coordination across the supply chain. - The company often uses BIM beyond its typical uses (e.g., design tools, bill of materials, erection sequence, etc.) to support logistic operations, such as BIM 5D characteristics (e.g., live cost analyses, construction efficiency, and budget tracking) along the supply chain. - In manufacturers' operations, the company can leverage BIM functionality to assist in standardizing the production of elements/modules (e.g., setting production times, component specifications, volumes, materials, panel optimization, connections). Furthermore, the company can often employ advanced algorithms to optimize production plans and schedules and use CITs, such as RFID, to record information, track production, analyze performance using gathered data, and monitor operator status to support manufacturing management. - BIM technologies often support site management by enabling the detection of element/module status, material/equipment status, and workers' distribution. Other auxiliary technologies, such as cameras and drones, are frequently used to support site management during the project execution. - The CITs is sometimes oriented toward controlling safety issues and risks in manufacturing and assembly operations, for example, by incorporating physiological sensors to monitor fatigue and heart health and RFID technologies to capture work conditions.

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