Universidade do Minho
Escola de Engenharia

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A framework for determining the ideal level of modularization for a construction project – Case study

March 2024

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Master Dissertation
Master in Industrial Engineering and Management

Work done under the guidance of
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March 2024

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Acknowledgements

I gratefully acknowledge everyone who supported me in completing this research project and my Master's degree in Industrial Engineering and Management at the University of Minho. Everyone who was a part of this journey provided invaluable guidance, support, and encouragement.

First, I would like to express my sincere appreciation to the supervisors of this investigation. Professors Maria Sameiro Carvalho and Carina Pimentel of the University of Minho provided insightful support and experienced guidance that assisted in shaping this academic research. This learning experience and the work that has been produced have been enhanced by their commitment to excellence and willingness to share technical knowledge. I would also like to acknowledge the support and mentorship of my supervisor at dst group, Cláudia Duarte. The industry experience, the ability to solve problems, and the capacity to guide the work towards the most valuable results were indispensable in adapting the systematic study to the working reality of a company in the sector in which it was developed. All of the insights provided priceless practical guidance that enhanced my academic learning.

I extend my gratitude to all the experts directly involved in this investigation and the engineer Sara Costa for their support, encouragement, and technical expertise, which were crucial for the development of the suggested tool and the daily achievements. The quality of this work has been significantly improved by the varied perspectives and contributions. Furthermore, I would like to express my sincere appreciation to the dst group for providing all the opportunities and resources necessary for conducting this investigation.

I also want to express my heartfelt gratitude to my family and boyfriend, whose unwavering belief in me and constant encouragement have been a driving force in my personal and academic development. All of their support and empathy throughout my academic path have been invaluable. Finally, I would like to mention my friends for their support and understanding throughout this demanding time, as well as all of the institutions that impacted my academic route, which led to this research project.

Integrity Declaration

I declare that I have acted with integrity in the preparation of this academic work and confirm that I have not resorted to the practice of plagiarism or any form of misuse or falsification of information or results in any of the steps leading to its preparation.

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Universidade do Minho, Braga, March 2024

Maria Alice da Silva Guerra

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Abstract

Construction Industrialization (CI) arises as an alternative to traditional construction methods and has had a substantial impact on the design, development, and management of Architecture, Engineering, and Construction (AEC) firms. Modular Integrated Construction (MiC) refers to a technique that increases project value through the export of the majority of site work to production plants. Nonetheless, the construction sector faces challenges in determining the ideal percentage of work that should be shifted offsite to optimize the overall supply chain performance. This research aims to bridge this gap by supporting the determination of the ideal level of modularization for the development of a construction project.

First, this study provides a comprehensive identification of industrialized construction project critical factors through a Systematic Literature Review (SLR). In total, 22 articles from the last 10 years (2014–2023) from the Scopus database were analysed. Another significant contribution is the implementation of a product architecture modularity decomposition approach—explored for the automotive industry—in the construction field to define different levels of modularization within a building unit. Given this and a review of the most cited construction supply chain performance evaluation methods, the primary contribution of this research is the definition of a conceptual framework to aid in determining the ideal level of modularization by assessing construction project supply chain performance. The proposed framework was validated through semi-structured interviews involving 11 experts with extensive construction cognitive and practical experience, along with a case study within the construction firm where the research was done.

The proposed framework is divided into three fundamental evaluation phases: project requirements assessment, company CI capability diagnosis, and performance results evaluation, as well as two intermediate steps: defining different levels of modularization within the construction unit of analysis and designing supply chains whose performance results should be assessed and compared. Thus, this research aims to assist businesses in deciding how to implement modularization, enabling them to move forward with CI.

Keywords Construction Industrialization, Modular integrated Construction, Conceptual framework, Systematic Literature Review, Supply Chain Performance evaluation.

Ferramenta para determinação do nível de modularização ideal para um projeto de construção – Estudo de caso

Resumo

A construção industrializada surge como alternativa à construção tradicional, com impacto significativo na conceção, desenvolvimento e gestão de empresas de arquitetura, engenharia e construção. A construção modular visa aumentar o valor do projeto, transferindo a maior parte do trabalho de estaleiro para unidades de produção. Contudo, enfrentam-se desafios na definição da percentagem ideal de trabalho que deve ser transferido para otimizar o desempenho da cadeia de abastecimento. Este estudo visa colmatar esta lacuna, auxiliando a definição do nível ideal de modularização para um projeto de construção.

Em primeiro lugar, apresentam-se fatores críticos da implementação de projetos de construção modular, resultantes de uma revisão sistemática da literatura. Foram analisados 22 artigos dos últimos 10 anos (2014–2023), disponíveis na base de dados Scopus. Outra contribuição do projeto prende-se com a implementação de uma abordagem de decomposição baseada na modularidade e arquitetura do produto — explorada para a indústria automóvel — no setor da construção, no sentido da definição de diferentes níveis de modularização para a unidade de construção em análise. Com base nestas contribuições e nos métodos de avaliação de desempenho de cadeias de abastecimentos mais citados na literatura, propõe-se uma ferramenta concetual que auxilie a definição do nível de modularização ideal para um projeto de construção, baseada na avaliação do desempenho da cadeia de abastecimento. A estrutura foi validada através de entrevistas semi-estruturadas com 11 especialistas com experiência no setor da construção, juntamente com um estudo de caso na empresa de construção onde o estudo foi desenvolvido.

A ferramenta divide-se em três fases fundamentais: análise dos requisitos do projeto, diagnóstico da capacidade de industrialização e avaliação dos resultados de desempenho, bem como duas etapas intermédias: definição de diferentes níveis de modularização e esboço de cadeias de abastecimento cujo desempenho deve ser avaliado e comparado. Assim, este estudo visa ajudar as empresas a decidir como implementar a modularização, permitindo-lhes avançar com a industrialização da construção.

Palavras-chave Industrialização da Construção, Construção Modular Integrada, Revisão Sistemática da Literatura, Ferramenta concetual, Avaliação de desempenho da cadeia de abastecimento.

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List of Abbreviations and Acronyms

AEC Architecture, Engineering, and Construction.

ASCM Association for Supply Chain Management.

BIM Building Information Modelling.

BOM Bill-of-Materials.

BOO Bill-of-Operations.

CI Construction Industrialization.

CMM Capability Maturity Model.

CSCMM Construction Supply Chain Maturity Model.

CTL Construction Team Leader.

DfA Design for Assembly.

DfM Design for Manufacturability.

DfMA Design for Manufacturability and Assembly.

DSM Design Structure Matrix.

EFQM European Foundation for Quality Management.

FD Finishing date.

GHG Greenhouse Gases.

HA Head of Architecture.

HBIM Head of BIM Officer.

HMC Head of Modular Construction.

HPP Head of Project Preparation Officer.

HVAC Heating, Ventilation, and Air Conditioning.

ILO International Labour Organization.

JIT Just-In-Time.

KPI Key Performance Indicator.

LSCM Logistics and Supply Chain Manager.

MEP Mechanical, Electrical and Plumbing.

MI Modular Index.

MiC Modular Integrated Construction.

NLR Narrative Literature Review.

PPE Personal Protective Equipment.

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

ProdM1 Production Manager 1.

ProdM2 Production Manager 2.

ProjM Project Manager.

QM Quality Manager.

SCM Supply Chain Management.

SCOR Supply Chain Operations Reference.

SD Starting date.

SLR Systematic Literature Review.

SM Safety Manager.

t.u. time units.

TQM Total Quality Management.

1 Introduction

This research project was developed in the Logistics department of the dst group, as part of the Master in Industrial Engineering and Management of the University of Minho.

This chapter aims to clarify the background and motivation for the development of a framework which aids to define the ideal level of modularization for construction projects, based on the performance of the related supply chain. Furthermore, the objectives and the research questions are exposed, as well as the research methodology used to achieve them.

1.1 Background

The construction industry significantly contributes to economic growth, putting nations in a better position to compete in global markets and improving inhabitants' quality of life (Tsz Wai et al., 2023). However, the global construction industry faces major challenges that highlight the need for performance improvement.

In order to obtain competitive advantage, construction companies must deliver projects on schedule and under budget without sacrificing the quality of the finished product (Lu & Liska, 2008). However, traditional onsite construction approaches are marked by high defect rates (Love et al., 2018) and the difficulty of meeting construction time and budget (Vaardini et al., 2016).

Waste associated with conventional construction projects is a result of delivery delays, flaws in the design stage, construction flaws which imply rework, adverse weather conditions and a non-functional work layout (Innella et al., 2019). Additionally, the division of tasks into smaller processes and their assignment to various suppliers and contractors exacerbates coordination issues between stakeholders and multiplies the number of non-value-adding components (Koskela, 2000), emphasising the significance of cycle time reduction and Supply Chain Management (SCM) in construction projects (Song & Daan, 2011).

In terms of environmental sustainability, the construction industry generates the highest percentages of waste in landfills in most countries and it is also accountable for high emissions brought on by excessive energy use. These factors led the Intergovernmental Panel on Climate Change to identify the building industry as one of the primary contributors to climate change, in 2007 (Wuni & Shen, 2019).

Additionally, despite the amount of the investments, the worldwide construction industry is regarded as one of the least productive and efficient. In fact, the fragmentation of the onsite building process creates a heavy dependence on the precedence of construction operations, which accounts for the industry's productivity growth of barely 1% per year on average, over the past 20 years (Wuni & Shen, 2019).

On the other hand, the sustainable existence of a labour-intensive business like building construction is threatened by shortages, shrinkage, and ageing of skilled labour in light of demographic trends around the world (Wuni & Shen, 2019; Blismas et al., 2006a).

Construction is also characterised by one-off, time-limited projects that depend on the site's location and surroundings and are carried out with the cooperation of several parties (Vrijhoef & Koskela, 2005). Due to the continuous supply chain fragmentation and reconfiguration, as well as the variability brought on by the large number of suppliers, the building system thus becomes more unpredictable than regulated production (Innella et al., 2019). In this sense, processes in construction are viewed as dynamic systems that are challenging to manage and control due to uncertainties and unforeseen events (Bertelsen, 2003).

Therefore, it is crucial that companies look at strategies of Construction Industrialization (CI) and SCM in order to counteract the sector's stagnation, enhance its performance, and assure its long-term sustainability. Thus, modular construction, which is still in its early stages of implementation, emerges as one innovative and sustainable alternative method for civil construction (Hussein et al., 2021; Jin et al., 2018).

In order to effectively meet the expanding demands of the global market, in 2022, the dst group and the Norman Foster Foundation formed an alliance to develop and promote modular construction and prefabrication solutions, establishing a new field of endeavour with novel challenges.

Offsite construction, when compared to traditional methods, allows for shorter construction times while improving the processes' quality, safety, and sustainability (Tsz Wai et al., 2023). However, one of the challenges of this type of construction is proper SCM (Hussein et al., 2021). Furthermore, considering "level of modularization" as the percentage of work done offsite[1], it is necessary to specify the right level and the components to which modularization should be applied (Sharafi et al., 2018). Thus, the evaluation of the supply chain performance, according to the level of modularization of a construction project, emerges as the motto for the work developed in the Logistics department of the dst group.

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[1] A project with a modularization level of roughly 10% is nearly exclusively traditional site-based construction, while an 80% level refers to a complete, fully furnished prefabricated building system (Sharafi et al., 2018).

1.2 Objectives and research questions

The primary objective of this project is the creation of a framework to support project designers choose the ideal level of modularization for a given project based on the performance of the supply chain involved, proving its applicability in a case study. As a result, the following sub-objectives were defined.

1. Identification of critical factors that influence the implementation and execution of industrialized construction projects;
2. Definition of an effective strategy for designing different levels of modularization within a building unit;
3. Definition of a supply chain performance evaluation system suitable for the decision-making process about the ideal level of modularization;
4. Creation of a conceptual framework for assessing supply chain performance which aids to determine the ideal level of modularization for a construction project;
5. Validation of the proposed framework in the context of a construction company.

In this manner, it is intended to address the following research questions:

1. Which factors affect the implementation and execution of industrialized construction projects?
2. How to define different levels of modularization within a industrialized construction project?
3. How can the performance of an industrialized construction project supply chain be assessed?
4. On the basis of the analysed factors and the current supply chain performance measurement methods, how can the most appropriate level of modularization be defined?

1.3 Research methods and approach

The conducted analysis began with a search for models or frameworks of comparison of supply chains linked to different levels of modularization in order to solve the identified research questions. Nevertheless, according to this investigation, there is a research gap in this field. Therefore, this study intends to fill this gap by combining findings from several approaches of analysis and performance evaluation systems that are currently being developed in a cohesive framework. Thus, this work is positioned in the realistic research paradigm that employ different methodologies in a single study (Hall, 2013).

Firstly, a literature review with two main focuses was conducted. After a brief contextualization of the current state of industrialized construction, a Systematic Literature Review (SLR) on the factors that affect the implementation and the performance of Modular Integrated Construction (MiC) projects, was carried out. In fact, this method has been used in the fields of construction engineering and management to specify the boundaries of current research and identify possible areas for further investigation. Without systematic reviews, theory development in this research domain would be constrained since the practise of rigid empiricism it naturally nurtures has long been a barrier to theoretical progress (Wuni & Shen, 2020a). Then, in order to cover a wide range of concerns about construction supply chain concepts and the most widespread and accepted supply chain performance evaluation techniques, it was conducted a Narrative Literature Review (NLR) on these topics. Although a NLR does not follow a rigidly defined process in terms of evidence search and study inclusion validity criteria, it provides a high-level overview of the study field, including major discoveries, hypotheses, and concepts, which is suitable to support the framework structure and measurement system (Collins & Fauser, 2005).

The conceptual framework structure is therefore the consequence of the combined outcomes of the literature review on modular construction critical factors and performance evaluation systems, and its basic functionality is divided into three distinct phases. Firstly, it should assist designers in defining potential modularization scenarios depending on the specific construction project requirements and component interactions. In a subsequent step, it should aid understanding of the company's capability necessary to develop the defined modular solutions. Finally, the supply chains associated with the development of the various modular solutions should be evaluated using a balanced technique that takes into account both short- and long-term, quantitative and qualitative, financial and non-financial components.

Then, semi-structured interviews were undertaken to adapt the literature-based framework to the practical environment, and a case study was developed to validate it.

The semi-structured interviews involved construction experts from the company where this project was carried out in order to support its development and adapt it. The interviewees were chosen based on their previous expertise with MiC and in the construction industry. The three main proposals of the conducted interviews were the validation of the framework structure, the identification of critical factors that influence the implementation of MiC projects, and indicators that allow the assessment and comparison of construction projects performance and therefore should be included in each framework dimension associated with each defined phase[2]. Thus, the interviews were designed around five research elements, shown in Table 1, which result in the interview protocol provided in Appendix B.

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[2] There are relevant evaluation dimensions linked with each stated framework phase, which should be assessed using various factors and indicators.

Table 1. Research elements of the conducted interviews.

Research elements	**Purpose**
Project context	Understand the relevance of the research topic.
Framework structure validation	Ensure the adjustment of the framework to the practical context of the design and planning processes of a construction project.
Modular solutions' definition	Identifying the factors that underpin the identification of structures with the potential to be industrialized.
Organization's CI capacity evaluation	Identification of factors that allow evaluation of the company's capacity to generate the industrialized solutions that it intends to develop.
Results evaluation approach	Identification of relevant factors for the evaluation and comparison of the performance of different development scenarios of a given MiC project.

Lastly, to validate the proposed framework, it is tested through its application to a real construction project context. As a result of comprehending the context of the ongoing MiC project in the dst group, the essential data was gathered to determine the possible levels of modularization and assess the company's CI capacity and supply chain performance of modular scenarios linked to those defined levels.

In sum, Figure 1 depicts the described research design framework for this investigation.

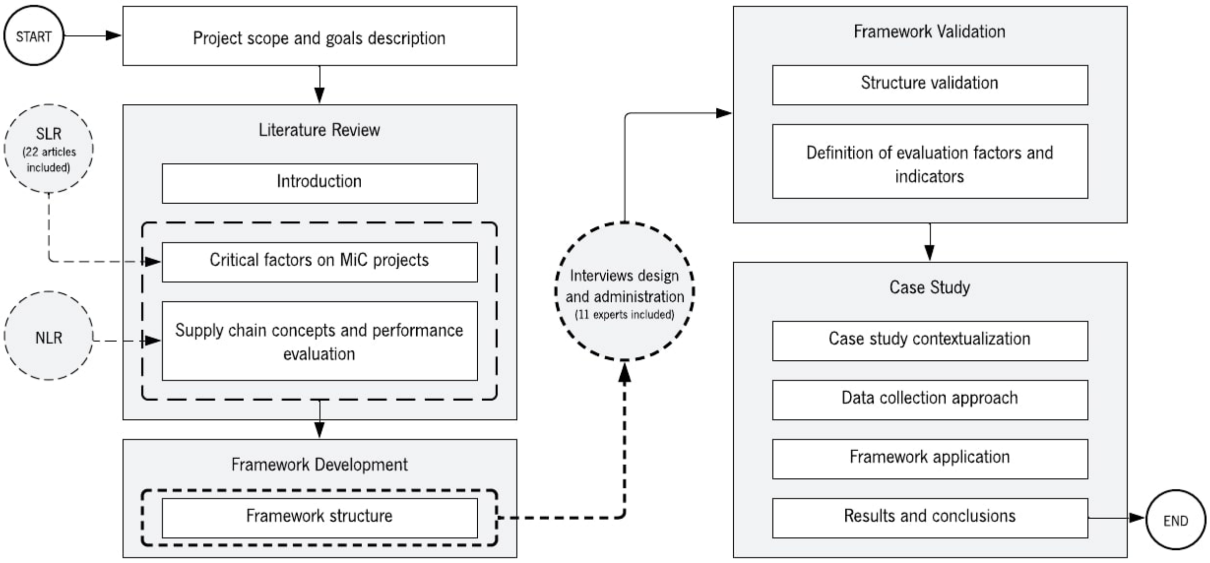

Figure 1. Methodological framework for the study.

1.4 Document structure

This section summarises this document structure, based on the presented research methodology.

Firstly, chapter 1 specifies the project scope, background, and motivation, the defined objectives and research questions, as well as the research approach devised to achieve them.

The literature review is then revealed in chapter 2 with the two previously specified key objectives: (1) contextualisation concerning CI, MiC projects, and their benefits, challenges, and critical aspects (sections 2.1 and 2.2), and (2) construction supply chain performance evaluation (section 2.3).

In chapter 3, a general structure for the suggested decision-making framework is offered based on the findings from the literature, the conducted interviews' results and direct observation of module development processes. This chapter reveals the framework structure and implementation method, describing and justifying each framework phase.

Then, chapter 4 pertains to a case study presentation of the framework application. To begin, the MiC project chosen to test the practical applicability of the decision-making framework, as well as the CI context of the organization in which this study was done, are presented. The proposed framework is then applied, taking into account the established implementation steps and the company's context, to demonstrate its viability. The case study results are then discussed.

Once the research phases have been completed, discussion on the proposed framework is depicted, and conclusions, research limitations and potential directions for future research are presented in chapter 5.

The research is further supported by four appendices: Appendix A presents the articles included in the conducted SLR; Appendix B relates to the interviews' development information, implementation protocol, and the corresponding results; and, to aid in comprehending the case study results, Appendix C exposes the analysis approach of a framework implementation phase and Appendix D details project scheduling assumptions for the development of the modular solutions under analysis in the case study.

2 Literature Review

The literature review on the relevant subjects is exposed throughout this chapter to contextualise the investigation and address the research objectives and questions.

As an introduction, it is described the broader environment in which industrialized construction solutions and, in particular, MiC projects, have emerged and developed. This section explains the key ideas and phases involved in implementing MiC projects, as well as its benefits and challenges. Furthermore, a SLR on critical factors of MiC projects is conducted.

Then, supply chain aspects in general and in the construction sector in particular are discussed. After this introduction, the most common and widely-accepted performance evaluation systems used for evaluating industrialized construction projects are explained to support the developed framework's structure.

2.1 Introduction

2.1.1 Construction industrialization

Since the last decades of the previous century, many researchers have focused on CI to address the challenges of the construction sector. In order to introduce production management theories in this industry, Koskela (1992, 1997) examined construction from the perspectives of transformation, flow, and value creation. Some production industry practices should be adopted when considering buildings as products that may be produced and assembled rather than as structures that must be constructed. Through the rationalization of value-added operations and the waste minimization, research on this topic has begun to focus on the identification and reduction of waste in construction, the exploration of flow improvement possibilities, towards the decrease of variability along the construction process, and process optimization. This results in final products with higher value that satisfy the needs of the clients (Innella et al., 2019).

As stated in section 1.1, uncertainties significantly impact the workflow of building projects. Indeed, labour availability, task interruptions, and component delivery delays are unpredictable factors that disrupt construction management. According to Koskela (2000), simplifying and standardizing processes may help to minimize the effects of uncertainty factors by reducing the complexity of supply and production flow.

Thus, CI develops from the necessity to search for advancements, and simplicity of existing processes through the use of prefabrication, mechanization, and robotics. To improve process performance, industrialized construction systems rely on innovative, disruptive, and integrated production techniques and technologies such as prefabrication, Internet of Things, Big Data, artificial intelligence, predictive analysis, Building Information Modelling (BIM), and virtual and augmented reality systems (Wuni et al., 2022d).

Furthermore, industrialized construction introduces the concepts of Lean Construction and automation, to increase productivity and the quality of processes and products (Brissi & Debs, 2019).

In order to offer a high-quality product that is produced with the goal of increasing value and avoiding waste, Lean Construction is focused on production planning and control. Therefore, taking into account Lean principles in the construction industry, this new paradigm allows the design and planning of the entire construction project, including site preparation, production, and assembly, the identification of repetitive activities, the implementation of standardized processes, and the active control of work flow. In this way, industrialized construction seeks to maintain a *pull* process while promoting the value of construction products, controlling the flow of information and materials, and monitoring the project schedule constantly. On the other hand, with regard to construction automation, the procedures mechanization is encouraged with a view to decreasing time, cost, and human error in construction projects (Brissi & Debs, 2019).

Therefore, the Architecture, Engineering, and Construction (AEC) industry started to investigate CI strategies, after decades of low productivity, underdigitalization, and limited appetite for innovation. Thus, it is witnessing a paradigm shift and a transition to industrialized construction, which is critical for establishing a position in dynamic and volatile markets (Costa et al., 2023; Zakaria et al., 2018a; Wuni & Shen, 2020a).

The way construction projects are developed, constructed, and managed is expected to change in this new paradigm. As a component of the CI movement, which has gained momentum in recent decades, offsite building has evolved as an approach of addressing some of the previously noted subpar performances that characterize conventional construction (Wuni & Shen, 2020a).

In this way, industrialized construction projects are designed to ensure that a significant portion of the work is completed offsite, with the finished products being transported to the construction site for assembly and installation (Wuni et al., 2022d). In fact, it is believed that shifting some tasks from the construction site to offsite production facilities may increase the project's value (Choi et al., 2019). Therefore, this type of project's planning entails a feasibility analysis, design, development, offsite component production, transportation to the site, and component installation (Wuni et al., 2022b).

Thus, the CI goes beyond a change in the process or product to show that the entire value chain is committed to a particular method of business management. In this sense, the transition process causes deep changes in the strategic planning of companies to implement a cohesive range of improvements, ensuring the success of the industrial transformation. These initiatives ought to primarily concentrate on production strategy, supply chain configuration, and lean transformation.

2.1.2 Modular Integrated Construction

MiC is one of the most researched offsite construction techniques that have arisen in recent years as alternatives to conventional procedures. This innovative approach replaces the fragmented linear construction, typically developed on the construction site, with an offsite integrated production of modules, which are then transported and installed onsite. This is considered the highest and most complete order of offsite construction, as 80 to 90% of the building unit is developed in a factory away from the construction site (Wuni & Shen, 2020a).

Modularity and modularization

In the electronics and automotive industries, the use of modularity to increase flexibility, lower costs, and reduce time-to-market has been successfully explored (Doran, 2004). Therefore, the construction industry has created modular solutions based on technology explored in these sectors, integrating the concepts of modularity and modularization into building construction.

Although there is no universal definition of modularity or modularization in this sector, a module can be defined as an independent unit or component of a modular system, with interfaces planned for assembly into a standardized architecture to form the building structure (Wuni & Shen, 2020a).

According to Langlois (2002), modularity is a general set of principles for managing complexity. By fragmenting a complex system into discrete components – modules – that communicate with each other, it is possible to eliminate systematic interconnections. Instead, modularity can be seen as an engineering concept that describes the extent to which modules can be produced separately and combined to provide flexibility and diversity of usage (Wuni & Shen, 2022f). According to the existing literature, there are several types of modularity that may be recognised, including: (1) bus modularity, in which all modules are interconnected via a single common module; (2) sectional modularity, in which product variants are constructed from particular arrangements of modules with a common interface; and (3) scalable modularity, in which some scalable components are combined with standard components (AlGeddawy & ElMaraghy, 2013), corresponding to the most relevant approach for MiC project. In this context, component production and assembly, non-volumetric and volumetric pre-assembly, and fully assembled modular construction are examples of the various approaches of modularization in MiC projects (Wuni & Shen, 2022f).

On the other hand, modularization is associated with products and processes standardization, which is the key element of industrialization techniques (Larsson et al., 2014). In the construction industry, it can be defined as the prefabrication of a complete system under controlled industrial conditions, which is then transported to the site, ensuring higher-quality projects and more effective resource management (Barbosa et al., 2017). Therefore, modularization entails large-scale modules that frequently need to be divided into smaller components to ease transportation to the construction site (Wuni & Shen, 2020a).

Thus, by addressing module architecture and design possibilities in addition to product-oriented production, modularization introduce the concept of mass customization of buildings (Larsson et al., 2014; Peltokorpi et al., 2018) and the supply chain configuration and organization (Doran & Giannakis, 2011).

Modular Integrated Construction Projects

Project design is the initial phase of a MiC project. Before the modules are constructed, a precise modular design must be prepared and approved in order to meet the project deadline (Wuni & Shen, 2020a).

As was previously noted, the development of MiC projects relies on a change in building's construction process. Therefore, construction should be understood as a product-oriented production process in order to enable the effective shift to the new paradigm of industrialized offsite construction (Larsson et al., 2014).

In this regard, in order to address the inefficiencies of onsite building activities, MiC projects are created in accordance with the Design for Manufacturability and Assembly (DfMA) philosophy (Wuni & Shen, 2022f).

DfMA combines Design for Manufacturability (DfM) and Design for Assembly (DfA) methodologies. In CI, DfM involves designing the project in a way that facilitates the production of the modular components, being concerned with the selection of the most cost-effective materials and processes, in order to minimize the complexity of production operations. On the other hand, DfA focuses on the design of the modules in order to facilitate their assembly, with the aim of minimizing the number of assembly operations and the associated costs. In this way, by designing construction projects according to the DfMA philosophy, it is possible to reduce the processes complexity. In fact, DfMA operates under the premise that if the design of the modules can be simplified, the modular components may be efficiently manufactured and assembled within the specified time frame and at a lower cost. In this way, construction projects can be continuously improved in terms of reduced production and assembly times and costs, product quality and reliability and worker safety (Wuni & Shen, 2022f).

Therefore, the Construction Industry Council claims that this construction strategy is focused on the simplicity of manufacture and effectiveness of modular assembly (Wuni & Shen, 2022f).

Additionally, in contrast to the conventional onsite paradigm, MiC projects accept simultaneous execution of construction work. In addition to the concurrent onsite preparation activities and factory production, there are operations that can be done simultaneously in the in-plant controlled environment (Wuni & Shen, 2022f). In this way, it is possible to reduce construction time even more and thereby increase project productivity (Barbosa et al., 2017). However, it requires extensive coordination of the modular supply chain, involving stakeholders not just before but also during the construction process.

After the production and assembly of the modules in a controlled factory environment, they are transported to the construction site for project completion, with the installation in the building under construction. Thus, a MiC project includes its design, ensuring all the required licenses and statutory approvals, for subsequent production, transport to the site and installation of the modules (Wuni & Shen, 2022f). Figure 2 depicts the sequence of the main stages of MiC project, presented in this section.

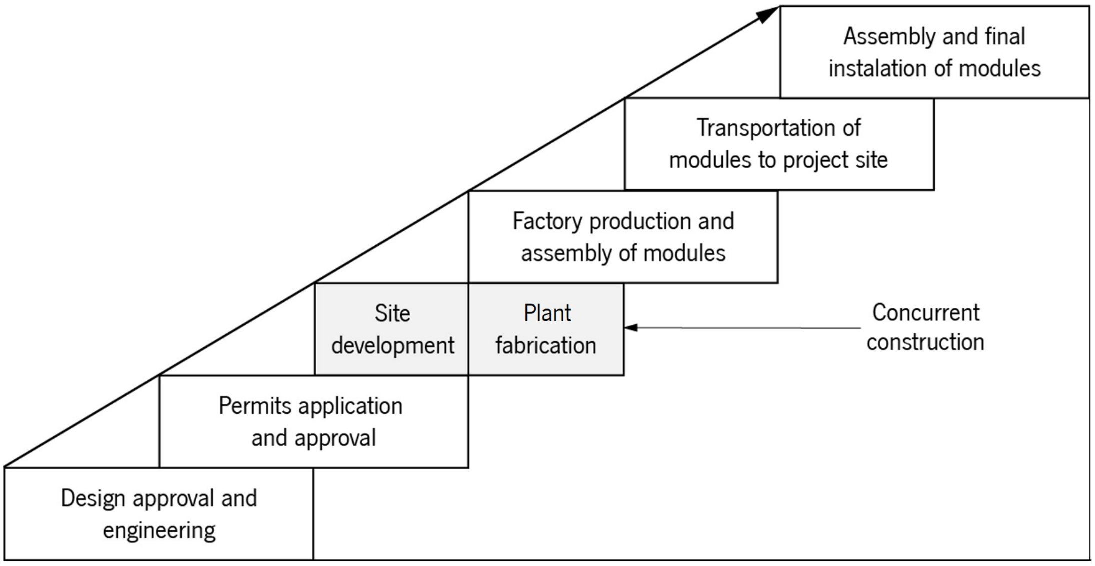

Figure 2. Stages of the MiC process.

(Wuni & Shen, 2022f)

2.1.3 Benefits and challenges of Modular Integrated Construction Projects

As previously stated, MiC applies the theories of modularity, modularization, DfMA, and lean manufacturing in order to design projects with improved cost-benefit ratios (Wuni & Shen, 2022f). In this regard, several studies suggest that, when properly applied, this construction technique typically leads to a reduction in time, construction waste and costs associated with the entire life cycle of construction. Furthermore, it enables improvements in the quality of projects, in the conditions of the working environment and in the productivity of construction activities (Wuni & Shen, 2020a). In this sense, in order to optimize the use of resources, it is crucial that the client and the end users (i.e., the occupants) understand the benefits of adopting MiC projects from an early stage (Tsz Wai et al., 2023).

However, this new paradigm also faces technical, financial and organizational challenges. Thus, it is imperative that companies looking to adopt MiC projects recognise these difficulties and calculate their impact on the effectiveness of the project and the organization. With this in mind, they should analyse if they have the necessary potential and commitment to develop modular projects. In fact, the achievement of the intended goals and the expectations of each participant, which vary for the customer, managers, engineers, employees, and contractors, actually determine the project success (Wuni & Shen, 2020a).

As a result, this subsection discusses some of the benefits and challenges of adopting MiC projects.

Shortening of construction time

Although clients in the construction sector aspire to quick delivery of projects, a large proportion exceed the stipulated deadlines, in some cases taking up to 120% of the set time (Barbosa et al., 2017). Since the conventional construction paradigm is relatively inelastic to short-term demand, the need to expedite building without sacrificing budget or project quality emerges (Wuni & Shen, 2019).

In this context, the advantages of MiC are highlighted by a number of authors when it comes to the project execution time. In fact, it is argued that offsite construction projects can lead to a 30–70% reduction in construction time (Wuni & Shen, 2019). The breadth of this range depends on the companies' and the area's state-of-the-art modular technology and project implementation. In countries where modular building is used more frequently, local businesses develop experience in the administration, planning, and construction of this sort of project, and workers become accustomed to the procedures for module assembly and installation (Tsz Wai et al., 2023). Thus, by decreasing the modules design, production, and installation times, it is possible to continuously improve the productivity of modular building projects.

The above-mentioned overlap between factory and site activities, schematised in Figure 3, also contributes to this decrease in construction time. The execution of concurrent activities, according to the MiC Display Centre, may reduce the duration of some projects' construction by roughly 30% (Tsz Wai et al., 2023).

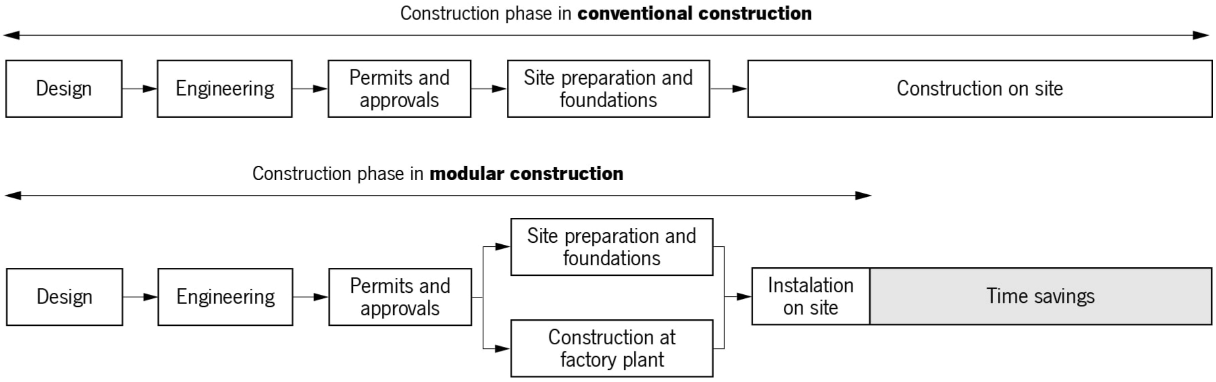

Figure 3. Time savings in modular construction.

(Kamali & Hewage, 2016)

Furthermore, the transfer of 80–90% of construction work to a controlled factory environment means that the vast majority of activities are not subject to the weather conditions, as is the case of conventional construction. In this way, work stoppages due to extreme adverse conditions are eliminated. On the other hand, the reduction in construction time on site reduces the incidence rate of vandalism and theft of materials on site, further reducing the possibility of delays in project delivery (Kamali & Hewage, 2017a).

Additionally, in the long-term, the execution of MiC projects enables companies to have greater certainty and predictability of construction time and project completion date (Wuni & Shen, 2019).

Cost reduction

In the short-term, when a company decides to adopt modular construction techniques, the cost of this approach may prove to be higher than the cost of maintaining the conventional methods with which it is familiar. In addition to the lack of experience, which implies training and a period of organizational adaptation, the costs associated with the production facilities must also be considered. However, in the long-term, the cost is expected to decrease as the scale of development expands. Some researchers estimate this reduction to be around 10% (Tsz Wai et al., 2023).

This decrease in the total cost is, in part, associated with the reduction of waste. It is estimated that the implementation of MiC techniques enables a 90% reduction in material waste, given the reuse and recycling opportunities provided by the development of activities in a controlled environment. This reduction can correspond to a decrease of about 4% in the project's overall cost (Tsz Wai et al., 2023).

Additionally, the production of the modules in offsite facilities allows a reduction in defects and, consequently, in the requirement for rework. In fact, it is said that MiC projects have rework rates of less than 1%. In this way, costs for materials and additional working hours are reduced. It should be noted that in more than 150 conventional construction projects in Hong Kong in 2001, it was proven that the cost of rework was around 4,4% of the overall construction cost (Tsz Wai et al., 2023).

Added to these factors is the decrease in costs associated with labour. This is provided by the transfer of activities to offsite facilities, as typically, in advanced economies, the cost of hiring labour for factory production is lower than that of hiring workers for onsite operations (Tsz Wai et al., 2023). Additionally, the cost of labour hours per project is impacted by the reduction in construction time.

In addition, the costs of transporting labour and construction equipment to the site are reduced. If more storage is available at the production site, material ordering costs are also reduced as larger quantities can be ordered and quantity discounts can be taken advantage of. In this way, the expenses related to site overload and congestion are also decreased (Kamali & Hewage, 2017a).

Lastly, it is believed that process simplification results in significant cost savings, enabling the project to meet the initial budget, in contrast with the conventional approach, in which many projects end 80% over budget (Wuni & Shen, 2019).

Improved quality

As previously indicated, MiC enables the reduction of construction defects since the majority of the activities are performed in a controlled environment and the processes and operations are standardized, automated, and more repeatable (Kamali & Hewage, 2017a). On the one hand, the controlled environment allows the maintenance of temperature and humidity conditions favourable to the characteristics of the materials used in the construction of the modules, eliminating exposure to meteorological disturbances. On the other hand, repeatability allows the skilled labour force working in modular production facilities to become familiar with and gain experience with the factory's equipment and processes (Tsz Wai et al., 2023).

Moreover, the adoption of innovative technologies for modelling construction information (BIM) and quality control tests at different phases of the process help to ensure construction accuracy and minimize errors (Lee et al., 2020). Finally, at the factory plant, prototypes can be developed, produced, checked, and tested before going into mass production (Wuni & Shen, 2019).

In the context of construction, quality can be quantified by the percentage of rework. Considering these factors, this percentage, which in the traditional context can account for up to 30% of the construction effort, is significantly reduced by transferring the activities to production facilities (Tsz Wai et al., 2023).

Improved safety

By decreasing the working time onsite, workers are less exposed to severe weather conditions as well as heavy work and dangerous activities (Kamali & Hewage, 2017a). These operations include work at height, most of which is now carried out at ground level when manufacturing modules offsite, significantly lowering the risk of workers falling. Furthermore, the presence of stagnant water and obstacles characteristic of the construction site are eliminated, reducing the risk of tripping or slipping. In fact, it is estimated that 80% of recorded construction accidents are eliminated in a factory environment (Tsz Wai et al., 2023).

On the other hand, the reduced demand for people onsite, as well as the resulting decreased congestion surrounding the building, make the working environment onsite safer for the workers assigned to the preparation and installation processes (Tsz Wai et al., 2023). Thus, this construction paradigm not only enhances the working conditions of factory workers but also the health and safety of the construction site.

Enhanced sustainability

The sustainability of MiC projects in terms of the environment, economy, and society has been demonstrated by numerous studies.

Despite the use of around 10–15% additional materials to ensure the structural strength required to safely transport the modules, this construction approach has superior environmental performance (Kamali & Hewage, 2017a). In fact, there is more efficient waste management through improved opportunities for waste control, reuse, recycling, and disposal in production centres. In contrast to the traditional approach, where a considerable amount of the waste generated is sent directly to landfills, modules can be used in new projects, dismantled, or refurbished at the end-of-life phase (Kamali & Hewage, 2017a).

Furthermore, less dust is produced when materials are transported to the site, less carbon emissions and Greenhouse Gases (GHG) are generated, and a less of carbon is incorporated (Tsz Wai et al., 2023).

Economic sustainability is related to the reductions provided in terms of time and costs and to the durability of modular buildings, while social sustainability is linked to improved health and safety conditions for workers, as well as diversity and inclusion, wage, and training labour aspects (Kamali & Hewage, 2017a). The economic and social sustainability impact of MiC project implementation is linked to cost reductions and improved safety benefits, which were already discussed.

Increased project planning complexity and early design freezing

The implementation of MiC projects faces challenges related to the need for enhanced planning at the design stage. Thus, these projects require a greater engineering effort and imply that the design be approved in advance (Kamali & Hewage, 2017a). In fact, before the construction of the modules begins, customers are required to accept a finalized design. As a result, it will be more challenging to suggest and implement changes to the specified planning and design at a later time (Tsz Wai et al., 2023).

Transport restrictions

From the perspective of transport, the materials are rarely sent directly to the construction site but are incorporated into the modules first. The modules are subsequently carried to the construction site on public roads, which requires exceptional precaution due to their massive proportions (Sharafi et al., 2018). Thus, due to the need for special licences for parts with high weight and volume, this transport may occasionally experience a delay in approval (Kamali & Hewage, 2017a).

Additionally, transportation restrictions can even render MiC projects invalid in certain regions, as the road network, especially in urban areas, is not designed to support such heavy loads (Tsz Wai et al., 2023).

Reduced storage capacity on site

With the transportation of components to the site comes the inherent challenges of storing them. Indeed, construction sites located in urban areas have limited space, requiring temporary storage sites (Li et al., 2014a). In this sense, the logistics of supplying materials and managing stocks and resources is essential since the execution process requires a Just-In-Time (JIT) delivery system.

Moreover, space constraints, exacerbated by the requirement for module storage capacity, might lead to complications in the installation process due to a lack of space for crane operation. In this way, site managers must ensure that the site is appropriately managed (Tsz Wai et al., 2023).

In order to realise the benefits and overcome the challenges of MiC projects, it can be argued that a prior examination of the modular product architecture should exist. In this regard, the following subsection delves into a commonly used approach for analysing the modular product design architecture.

2.1.4 Modular product architecture

As the structure and functionality of a product's interfaces are determined by its architecture, it is relevant to examine product architecture concepts when considering building components as modular products. Analysing the architecture of a product makes it easier to plan, test, and design how those components will be manufactured and supplied in more detail. In fact, modular architecture specifies the proper product structure, which is made up of a group of modules with distinct functions and minimal interaction with the rest of the product (AlGeddawy & ElMaraghy, 2013). In a fully modular architecture, the relationships between the parts within an assembly are concealed from the elements outside the assembly and the elements are grouped into distinct clusters. This is based on the idea that a module comprises more relationships between its constituents than relationships to elements outside the module (Yu et al., 2007).

In other words, product architecture is the method used to arrange a product's broken-down components into modules. Therefore, finding highly engaging groupings of components and clustering them into modules is necessary for the creation of modular product architecture (Yu et al., 2007).

In this sense, analysing the product architecture of a building module should be the first stage when defining levels of modularization, which is included on this project's scope. In a product architecture context, the level of modularization is linked to the level of granularity (or level of detailed description) of the modular product (Figure 4). The level of detail or granularity of an architecture is determined by the depth of its hierarchy of components, modules, and sub-assemblies, and it has significant implications for all subsequent activities throughout the product life cycle. In fact, the ability to achieve economies of scale by combining scalable components is dependent on the proper identification of common and diverse modules, as well as their interconnections. Therefore, when creating product families, the proper amount of aggregation and granularity should be carefully evaluated (AlGeddawy & ElMaraghy, 2013).

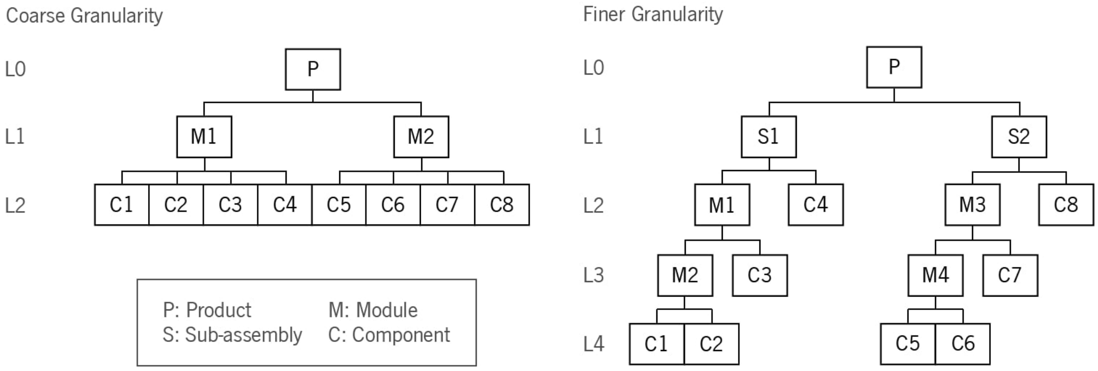

Figure 4. Different levels of product architecture granularity.

(AlGeddawy & ElMaraghy, 2013)

Zeng and Gu (1999) suggested that the links between the product components and related assembly tasks may be expressed by extending the product structure tree to express its architecture. Complex construction modules should thus be modelled for the purposes of decomposition and integration. Furthermore, in engineering design, “matrix-based design structuring” refers to the use of a matrix to capture the dependencies between elements (Deng et al., 2012). The Design Structure Matrix (DSM) is a recognized technique used in product architecture for breaking down and depicting relationships between components of a product.

During the 1990s, DSM applications significantly increased in both research and industrial practise. This tool has started to be used in a variety of industries, including building construction, semiconductor manufacturing, automotive, photography, aircraft, telecommunications, small-scale manufacturing, factory equipment, and electronics (Browning, 2001). Within the offsite construction context, in 2021, Hussein et al. conduct a systematic review on the modelling of offsite construction supply chain to identify trends and gaps, and hence, highlight future research opportunities. Regarding design problems associated to MiC projects, the authors identified DSM as an explored method to deal with architectural design in building projects. In fact, a DSM can present connections between system components in a condensed, illustrative, and analytically format in a square matrix with the same labels for rows and columns (Browning, 2001).

As described in Table 2, there are two main groups of DSMs: static and time-based. A static DSM describes concurrent system components like organizational groupings or the components of a product architecture, which is the case in this project analysis. More specifically, component-based DSM is commonly used by systems engineers to represent architectural components and interfaces based on subsystems relationships, facilitating both systemization and innovation (Browning, 2001; Deng et al., 2012). Therefore, a crucial element of modular construction is the use of component-based design, in which buildings or other structures are built from prefabricated components that are produced offsite and assembled onsite.

Table 2. Summary of DSM type characteristics.
(Browning, 2001; Deng et al., 2012)

Category	**Type**	**Representation**	**Application**	**Integration**
Static	Component-based	Components in a product architecture and their relationships	System architecture, engineering, design, ect.	Clustering
	Team-based	Organizational unit relationships	Organization design, interface management, application of appropriate integrative mechanisms	
Time-based	Activity-based	Activity input/output relationships	Project scheduling activity sequencing, cycle time reduction, risk reduction, etc.	Sequencing
	Parameter-based	Design parameter relationships	Low-level process sequencing and integration	

In graph representation, because diagonal elements have no relevance, they are generally blacked out-/shaded (or used to record some element-specific attribute), as seen in Figure 5(a). Furthermore, interactions between elements are typically indicated by binary codification, with an off-diagonal black cell, an "X" mark, or "1" indicating a relationship between components and a blank cell, or "0", indicating a lack of one. In a general DSM representation, reading across a row exposes what other elements the element in that row provides to; scrolling down a column tells what other elements the element in that column depends on. Reading along a column provides input sources, but reading across a row reveals output sinks (Yu et al., 2007). Consider a conceptual architecture diagram in which nodes represent components of a product or system (corresponding to the column and row headings in the matrix) and arrows represent relationships between components (represented by the marks inside the matrix). If an arrow connects element C to element A, a mark is placed in row A and column C on the DSM[1].

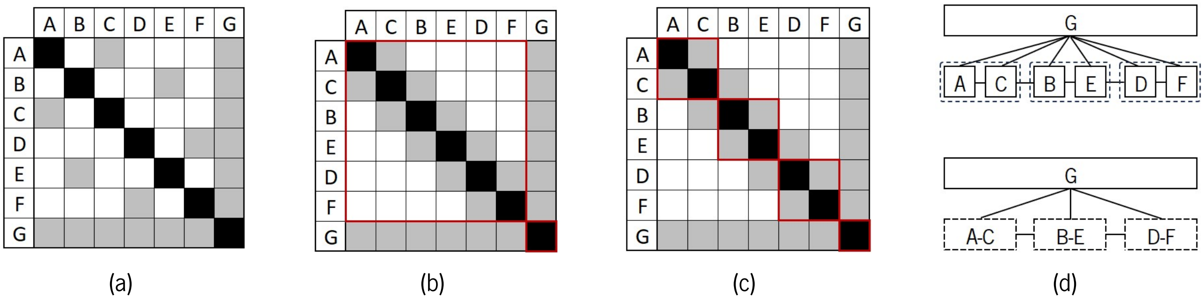

Figure 5. DSM clustering example: (a) original DSM, (b) clustered DSM, (c) alternative clustering, and (d) conceptual architectural diagram.

(adapted from Yu et al. (2007))

After creating the DSM for a product, it can be analysed for module identification (clustering). DSM clustering seeks subsets of DSM elements (i.e., clusters or modules) that are mutually exclusive or interact minimally. In other words, clusters internally include the majority of the interactions, while interactions between clusters are deleted or minimised (Yu et al., 2007).

Consider the presented DSM as an example. As seen in Figure 5(b), the original DSM was modified to concentrate the majority of the interactions within two distinct blocks or modules: ACBEDF and G, by simply swapping the order of the rows and columns. Nevertheless, there are some elements with no relation within the forming clusters. Then, Figure 5(c) points to the development of four clusters with maximum interaction between their components: AC, BE, DF and G, which is illustrated in conceptual architecture diagram presented in Figure 5(d). Additionally, several different combinations could be considered: AC

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[1] It should be noted that component-based DSMs often contain "symmetric" data since they show non-time-based component interactions in response to inquiries as "Do these components interact?"(Browning, 2001).

and DE can be concatenated into modules, the sequence A through F can be thought of as a single super module, an intermediate module DE can be sandwiched between modules AC and DF, or the sequence A through F can simply be stated as consisting of the primitives A through F with the bus G (Yu et al., 2007). Thus, it is demonstrated that there are numerous options for clustering product components into modules, and it should be investigated how to adapt this arrangement to the product architecture.

The approach offered by AlGeddawy and ElMaraghy (2013) to identify the modular potential of a product design by finding the optimum granularity level and number of modules is reviewed in this section. This technique was tested in the automotive industry to establish its capabilities and high quality of results, and it is still acknowledged by multiple authors in different operating fields[2]. Although no references to the application of this approach in the MiC context were identified, it is thought to be worth investigating.

According to the authors, hierarchical clustering must be used to construct a product architecture and set the modules that best partition a DSM into modular architecture. This might be disclosed through a cladogram representation built on DSM interactions and on product Bill-of-Materials (BOM) or Bill-of-Operations (BOO). Cladistics – a categorization tool widely used in biology to reveal the evolution hypothesis and speciation scheme of a set of entities – was used in the field of artefacts to expose the evolution and co-development of products and production systems. This graphical cluster representation categorises items based on their features. However, the authors modified the cladogram construction for DSM clustering to show interactions between components, which are treated as their features. For accurate findings, the "1" diagonal elements of the original DSM in Figure 6 account for the self-relationships of components to themselves. The cladogram reveals the suggested hierarchical architecture of such components, beginning with a common root that represents the entire product and ending with terminals for individual components. The long, inclined line on the left side, at each branching node, denotes the start of a new granularity level. The resulting tree describes the product architecture, while its depth shows its granularity. The example in Figure 6 shows three granularity levels below each branching node. The lowest node of individual components is dismissed as it does not provide valuable modularity data (AlGeddawy & ElMaraghy, 2013).

The optimal level of granularity minimizes external interactions between clusters and maximizes internal dependencies (AlGeddawy & ElMaraghy, 2013). Thus, it is suggested to base the clustering process on the ordered and clustered DSM built on each granularity level of the clustering tree, considering a Modular Index (MI) approach, with the goals of (1) minimizing interactions between modules and (2) maximizing internal integration. Given the DSM graphic representation, the first objective is translated to minimize the

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[2] This study has received 76 citations between 2013 and 2023.

number of dark cells outside the established cluster, while the second is to minimize the number of blank cells within the designated clusters. Considering that dark cells represent "1" elements and blank cells correspond to "0", the authors defined MI as the sum of the number of inter-relationships among modules and the number of missed intra-relationships among components of these modules, being expressed as:

$$MI = I + Z, \tag{2.1}$$

where I is the number of "1" (dark) elements in the DSM outside developed clusters, and Z is the "0" (blank) elements of those clusters. In light of this, it is simple to realise that the best clustering occurs when the MI is the smallest. Thus, the MI must be calculated for each granularity level to determine which one optimizes the interfaces between clusters, by optimizing the system modularity (AlGeddawy & ElMaraghy, 2013). The optimum granularity map, which serves as the foundation for designing the optimal product architecture and modules, is represented by a cladogram with the optimal granularity depth.

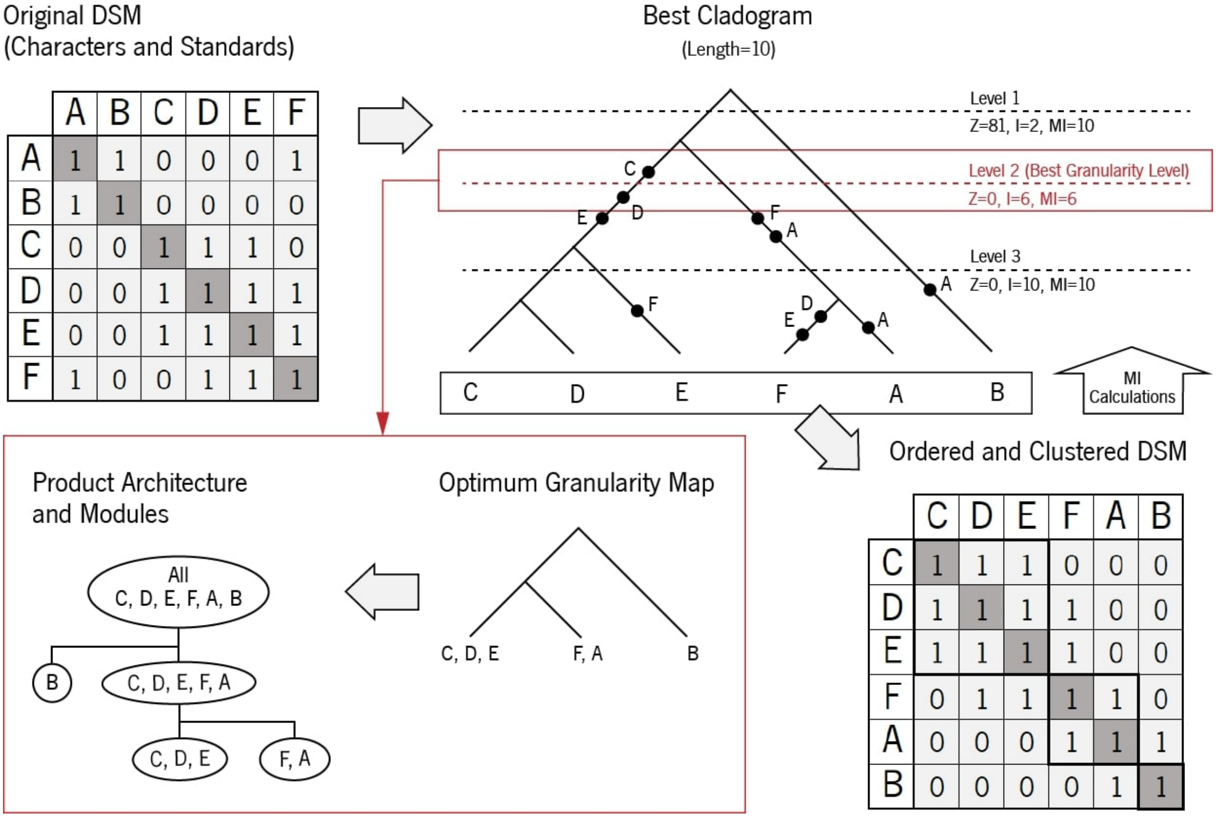

Figure 6. The DSM clustering model steps proposed by the authors.

(AlGeddawy & ElMaraghy, 2013)

Given the benefits and challenges stated, and the presented approach to deal with a modular product architecture, it can be argued that a number of critical factors must be considered while employing industrialized methodologies to accomplish the aims of MiC project execution.

2.2 Critical factors of modular construction projects

Critical factors are the main aspects that should be prioritised in order to achieve project success and reduce project failures. As such, they have received a profound attention of construction management researchers (Wuni & Shen, 2020a). In this manner, in order to develop a framework which takes into account the important aspects that have an impact on the execution and performance of MiC projects, a **SLR** on this topic was conducted with two main focus: (1) critical factors for the implementation of MiC projects and (2) factors that affect these projects' performance.

In **data identification** stage, the preliminary research on CI and MiC projects was crucial to determine the most relevant keywords specific enough to bring only studies linked to the topic. Then, the search process was carried on Scopus scholarly database, as it is commonly used for screening data sources and proven to produce reasonably extensive results. It was conducted under the field "Title" with a string containing three levels of keywords, shown in Table 3, which aims to address the systematic literature review's first objective, and independently with another string with two keyword levels, presented in Table 4, that relates to the second literature review focus. The "Abstract" and "Keywords" fields were not considered to accelerate the identification of factors in the project development context and time horizon.

For both strings, the first level of keywords is related with the interchangeable terms to identify the construction paradigm in analysis. In addiction to the terms associated with offsite industrialized and modular construction, the terms "modular" and "modularization" separately were considered as modularization studies in different areas could prove equally interesting for the analysis developed. Considering the first string, the second level of keywords outlines the focus on the identification of the factors that influence, enhance and support the implementation of industrialized solutions. Then, it was considered a third level to narrow down the analysis to only critical and decision factors, which might be established in a framework. For the second string, the second level of keywords outlines the focus on factors commonly used to assess the performance of industrialized projects.

Table 3. Keywords list used in the identification of critical factors.

Level	**Keywords**
Production paradigm keywords	"offsite construction" OR "modular integrated construction" OR "industrialized construction" OR "modularization" OR "modular"
Factors keywords	"factors" OR "enablers" OR "drivers" OR "benefits" OR "support"
Analysis keywords	"critical" OR "decision analysis" OR "framework"

Table 4. Keywords list used in the identification of performance indicators.

Level	**Keywords**
Production paradigm keywords	“offsite construction” OR “modular integrated construction” OR “industrialized construction” OR “modularization” OR “modular”
Performance keywords	“performance assessment” OR “performance evaluation” OR “performance criteria” OR “key performance indicators”

Then, the **data screening** stage might clearly define the research boundaries and produce high-quality knowledge generation. In this manner, three research constraints were established, which narrowed the investigation to studies (1) published and written in English, and (2) from 2014 to 2023, (3) within the “Engineering” subject area. Additionally, the title and abstract of the collected studies were analysed to investigate whether or not they fell within the project scope. With this goal, studies which employ modular concepts with a different meaning of the considered in this analysis (e.g., software, methodologies, or communication networks modules) were excluded based on title and abstract. Since the search revealed no publications examining modularization in other industries, contrary to expectations, only studies on industrialized solutions in construction field were included. Thus, for the first string, a total of 20 studies were selected for full-text assessment, whilst for the second, the number of studies was reduced to 24.

In the **eligibility** stage, to determine which papers to include in the study sample, a full-text analysis was carried out. In this stage, only studies that address the research questions were considered: studies which (1) explore factors that influence the implementation of the industrialized construction projects, or (2) that affect their general performance. Considering the search based on the second string, papers that only analyse standard deviations of a particular aspect of structural performance were disqualified. Also, 3 articles must be regrettably disregarded since the full-text access was not available. Thus, 17 studies accessed by the first string and 5 studies found with the second one were included in the following analysis.

As a result of this procedure, whose simplified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart is depicted in Figure 7, 22 studies were included in the conducted review. A list with the included studies is presented in Appendix A[3].

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[3] Column *No.* is used to identify the articles in this section

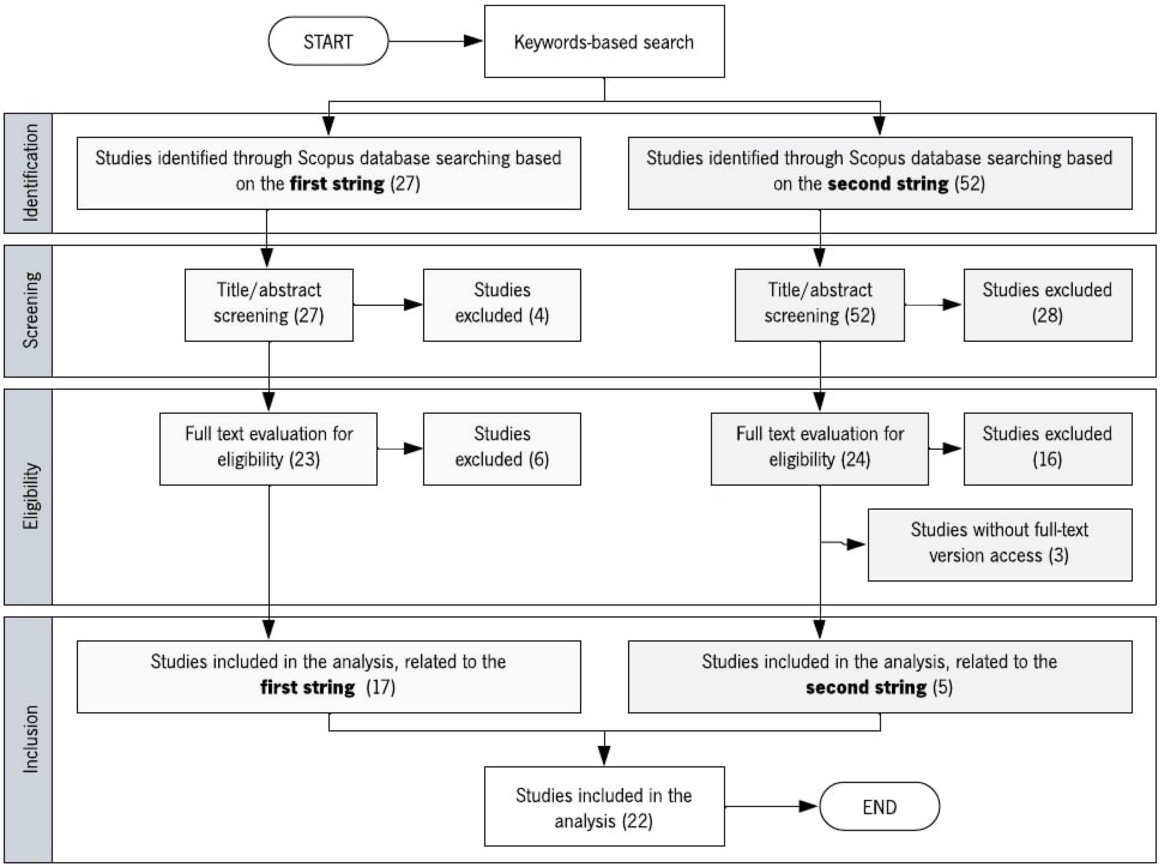

Figure 7. PRISMA flowchart.

Critical factor analysis

From the included studies, there were extracted 651 individual factors. Then, considering the context of development, the pertinent factors for analysing the implementation of a MiC project and the performance of the related supply chain were selected. In order to do this, ten suitable categories were created based on the categories commonly identified in the analysed studies and a preliminary general analysis of the collected factors: (1) “project requirements”, (2) “culture and leardership”, (3) “planning and control”, (4) “supply chain coordination”, (5) “modelling technology”, and (6) “time”, (7) “cost”, (8) “quality”, (9) “safety” and (10) “environmental sustainability” performance. Then, the factors with similar meanings were grouped, after manual coding. The coded factors were continuously compared with the established categories in order to fill them. A factor’s applicability for the analysis was determined by comparing it to the already-existing categories. If it fits one of them, it should be checked if this factor has already been added or if a factor with a similar meaning already exists. If this is the case, a new bibliography reference should be added, and it should be analysed if the factor needs to be adjusted. On the other hand, a new category of factors should be added if a certain factor does not fit into any category, but is still significant in the context of the defined framework. Figure 8 depicts the factor analysis process.

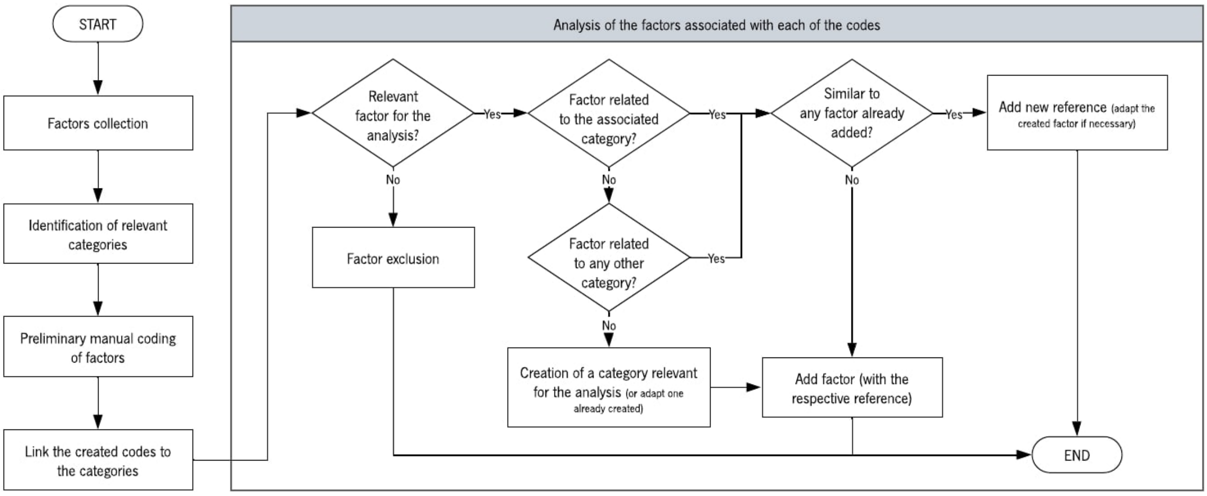

Figure 8. Factor analysis process.

An example based on some collected factors is presented to enhance knowledge of this technique. For this example, a simple code was chosen. As one of the above-mentioned challenges of industrialized construction projects are the transport restrictions, it is a commonly mentioned aspect in the analysed studies. Thus, one of the created codes was "transport" and Table 5 shows some of the factors that were associated to it. Not all the factors related to this code were listed to make this explanation easier. Note that although there were factors related to "transportation costs" and "transportation lead time", they were assumed as elements of other codes: "cost" and "time", respectively.

Table 5. Some factors associated to "transport"code.

Created code	Factor	Reference
Transport	Transportation method	[3]
	Road network capacity and capability	[3]
	Distance between site and factory	[3]
	Transportation regulations	[4]
	Limited capacity of infrastructure and transportation modes	[5]
	Availability of sound transport infrastructure and equipment	[6]
	Availability of local transport infrastructure, equipment, heavy lift and site transport capability	[11]
	Easy delivery/supply of components to the site	[16]

After the manual codification of all the factors connected to the transportation aspect, this code was assigned to the category “planning and control” since it is related to the capability of the construction system and, thus, influences its scheduling and monitoring. However, because additional factors influence project planning and control, a subcategory named “Transportation aspect” was formed. To begin filling this subcategory, the “Transportation method” factor and the corresponding reference were added. Considering the second component (“Road network capacity and capability”) it is easy to understand that it is linked to the chosen transportation method. As a result, the previously added factor was renamed “Transport constraint (method and capacity)”. Because both components were collected from the same study, the reference was kept. Following that, the “Distance between site and factory” factor was introduced as a new factor connected with this subcategory with the associated reference. As the following four factors refer to other transportation restrictions, the first factor was renamed “Transport constraints (permits, methods, capacity, and infrastructure)” and the associated references were added to it. Finally, although the last component is similarly related to transportation, it was determined that it was more concerned with the efficiency of the transportation process than its planning and control. As a result, a new category called “process efficiency” was introduced to account for the “frequency of deliveries to the site” factor.

Following this process, beyond the categories defined initially, “process efficiency” and “module design considerations” were created. As mentioned, the first one refers to factors that affect the efficiency of the processes. The other additional category reveals decision-making factors that support the development of tools to aid in the decision about the level of industrialization best suited to the setting of a project. Taking everything into account, Table 6 displays the 94 factors distributed by 12 categories that emerged from this review. Table A.2 in Appendix A lists the articles that refer to each of the factors, which are identified by the reference number defined in Table A.1.

Table 6. Factors that affect the implementation and performance of MiC projects.

Code	Factor	Code	Factor
D1	**Project requirements**	**D6**	**Process efficiency**
1.1	Client receptivity to industrialized solutions	6.1	Labour and equipment productivity
1.2	Client and market requirements	6.2	Frequency of deliveries to the site and traffic movement
1.3	MiC design codes and standards	6.3	Process complexity/standardization
1.4	Project scope and defined parameters (uniqueness, public exposure)	6.4	Production waste
1.5	Assembly tolerances of components and modules	**D7**	**Time performance**
1.6	Repeatability in design	7.1	Project schedule
1.7	Ability to achieve economies of scale	7.2	Project completion time
1.8	Early material and design freezing	7.3	Certainty in project completion time
D2	**Culture and leadership**	7.4	Design time
2.1	Appropriate business strategies and competitiveness	7.5	Production time
2.2	Availability of financial and technical support and training	7.6	Construction time
2.3	Availability of skilled management and supervising team	7.7	Down time for testing
2.4	Capacity and experience in CI projects	7.8	Delivery time
2.5	Commitment and involvement throughout the project	7.9	Transportation time
2.6	Culture of communication and collaboration	7.10	Assembly time (module-to-module/frame alignment)
2.7	Global containment of contracts, risk and conflicts	**D8**	**Cost performance**
2.8	Top management support in decision making	8.1	Project budget
D3	**Planning and control**	8.2	Operation and maintenance costs
D3.1	**Offsite capacity**	8.3	Cost certainty/conformity
3.1.1	Availability of skilled workforce	8.4	Design costs
3.1.2	Ability to handle and lift equipment and modules	8.5	Initial cost
3.1.3	Factory layout (including storage capacity)	8.6	Equipment costs
3.1.4	Availability of resources (materials and equipment)	8.7	Labour costs
3.1.5	Production technology/automation for CI	8.8	Material/inventory costs
3.1.6	Raw material delivery rate	8.9	Transportation costs
D3.2	**Location and site attributes**	8.10	Installation and assembly costs
3.2.1	Site accessibility	8.11	Other logistics costs
3.2.2	Licenses for the site	8.12	Other construction and production costs
3.2.3	Site conditions, constraints and characteristics[4]	**D9**	**Quality performance**
3.2.4	Site location	9.1	Construction and production quality
D3.3	**Onsite activities**	9.2	Defects and rework and repairing
3.3.1	Availability of skilled workforce	9.3	Quality of products[5]
3.3.2	Onsite activities management	9.4	Quality control
3.3.3	Onsite disruptions and delays	**D10**	**Safety performance**
3.3.4	Quality and availability of construction equipment	10.1	Building safety (health and security of occupants)
D3.4	**Transportation aspects**	10.2	Construction accidents
3.4.1	Distance between site and factory	10.3	Exposure to risks and hazards
3.4.2	Transport constraints (permits, method, capacity and infrastructure)	10.4	Exposure to severe weather conditions[6]
D4	**Supply chain coordination**	10.5	Health and safety management in the workplace
4.1	Availability of manufacturers and suppliers	**D11**	**Environmental sustainability performance**
4.2	Supply chain capacity for CI	11.1	Carbon emissions and embedded carbon
4.3	Supply chain management and integration/alignment	11.2	Compliance with environmental standards and certifications
4.4	Extensive project planning and scheduling	11.3	Construction water footprint
4.5	Real time supply chain execution and monitoring	11.4	Consumption of materials
4.6	Management of on-site and offsite construction activities	11.5	Energy efficiency/Energy consumption/Incorporated energy
4.7	Inventory management and control (avoid onsite shortage of modules)	11.6	Site and community disturbance (noise)
D5	**Modelling Technology**	11.7	GHG emissions
5.1	Accurate design and engineering specifications	11.8	Level of pollutants/building dust
5.2	Design adaptation for modularization and DfMA	11.9	Volume of recycled/reused materials/sites
5.3	Presence of relevant supportive technology (BIM)	11.10	Waste generation
D12	**Module design considerations**		
12.1	Alignment on MiC project drivers and module architecture	12.4	Early advice from MiC design professionals and experts
12.2	Effect of module size on the processes planning	12.5	Key decisions understanding and made as early as possible between all parties involved
12.3	Preliminary definition of the most appropriate module size and type		

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[4] Includes site layout and space for unloading and storing modules, handling the materials and cranes, considering height and loading restrictions on site.

[5] Considering finishes, stability, integrity and structural performance of the modules, mechanical, electrical and plumbing coordination.

[6] Also affects the project schedule and quality of the finished product.

Given these factors, it can be argued that planning and control strategies should be designed for configuring and optimizing processes, ensuring that the project runs efficiently and effectively (Wuni & Shen, 2020a). In other words, it is crucial to ensure proper SCM to improve organizational competitiveness of CI solutions, as noted in the literature, proving the relevance of the topic addressed by the proposed framework.

Thus, the next subsection investigates and clarifies concepts connected to the supply chain, its management, and performance evaluation, both in general and in the context of the construction industry.

2.3 Supply Chain concepts and Performance Evaluation

2.3.1 Supply chain

The supply chain is the network of organizations involved in the activities that create value for the customer in the form of products and services through upstream and downstream links (Vrijhoef & Koskela, 2000).

From information and material perspective, Beamon (1998) defined the supply chain as the set of flows and transformations in an integrated manufacturing process, which converts raw materials into finished products that are then distributed to customers. In this context, different organizations may be in charge of manufacturing components, assembling products, or marketing them (Higginson & Bookbinder, 2005).

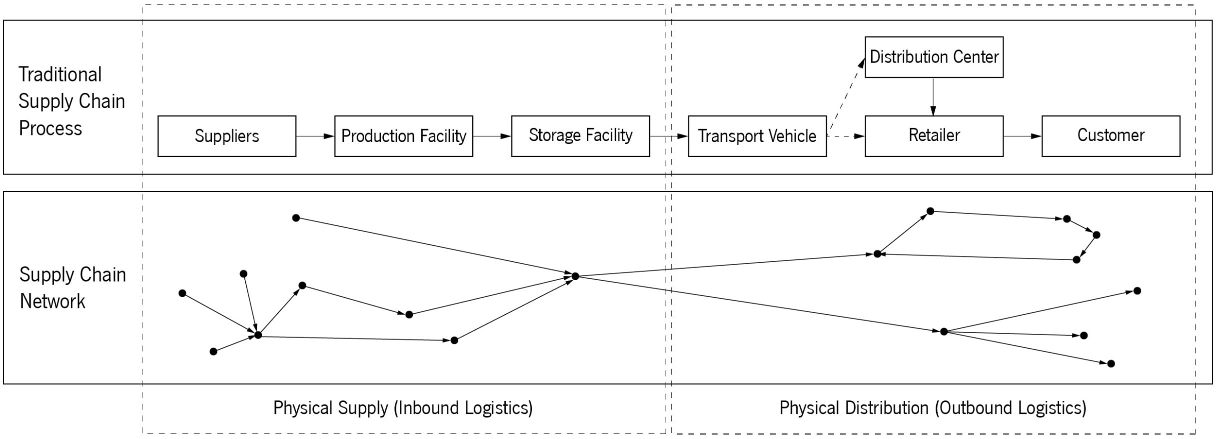

Figure 9. Generic representation of a supply chain.

(adapted from Beamon (1998) and Carvalho (2012))

According to recent literature, rather of being considered as a chain, it is seen as a network (Figure 9) which includes a variety of facilities, each of which performs a distinct task in the network (Govindan et al., 2017). In this perspective, a company is seen in the centre of a network of suppliers and customers (Christopher, 2011) and there are identified different layers (also known as echelons) for defining a group of facilities that perform the same task and are of the same type. Considering this, suppliers, plants, distribution centres, warehouses, and customers are the basic layers of supply chain networks, and material movements are frequently from suppliers to customers (Govindan et al., 2017). In addition, various material flows can be identified: (1) single-sourcing, which indicates that a facility or a customer can only be served by one facility from its upstream layer; (2) intra-layer flows; and (3) direct flows from upper levels to customers. Figure 10 depicts these material flows for a typical supply chain network (Govindan et al., 2017).

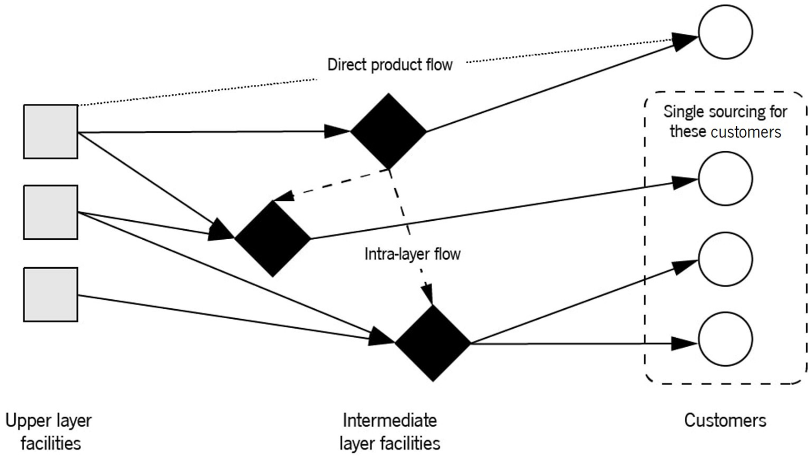

Figure 10. Generic representation of a supply chain.

(Govindan et al., 2017)

As seen, the transformation and transfer processes, at its highest level, is comprised of two basic, integrated processes: (1) the production planning and inventory control processes – Inbound Logistics or Physical Supply –, and (2) the distribution and logistics processes – Outbound Logistics or Physical Distribution. The first one includes the interfaces between the manufacturing and storage processes. Production planning encompasses the design and administration of the manufacturing process, including raw material acquisition, production scheduling, and materials flow control, while inventory control refers to the planning and management of the rules and practices for storing components. The second one determines and manages how products are transported from the warehouse and delivered to retailers. These goods may be delivered directly, or they may be moved to distribution centres in the first place (Beamon, 1998).

Due to the various configuration options, a firm may also be part of multiple networks. Thus, the complexity associated with the supply chain processes and relationships leads to the need for logistics management and support of storage, order administration, and transportation activities (Higginson & Bookbinder, 2005).

In this sense, the notion of SCM emerged in the manufacturing sector. Its first manifestations evolved with the JIT delivery system, as part of the Toyota Production System, to regulate deliveries and ensure production in the right quantity at the right time (Vrijhoef & Koskela, 2000).

The Global Supply Chain Forum defines SCM as the integration of the main business processes, from the end user to the suppliers of products, services, and information that add value to the customer and other stakeholders in the process. Thus, in order to meet consumer demands, logistics is crucial as part of this management in the planning, implementation, and control of the flow and storage of materials, services, and information between points of origin and consumption (Lambert & Cooper, 2000).

Therefore, the SCM challenges include guaranteeing information transparency, integrating all parties, reducing variability, synchronising material flows, managing and controlling resources, and constantly improving its configuration (Vrijhoef & Koskela, 2000).

2.3.2 Conventional vs. industrialized construction supply chain

In the construction industry, a supply chain is referred to as a network of facilities and processes that add value and are involved in project design, contract management, procurement of services and materials, and production and delivery of materials to the construction site (Love et al., 2004).

Figure 11 outlines the typical configuration of a **conventional construction supply chain**. As shown, in addition to the main contractor, there are several entities involved in the project execution. In this context, the involvement of all parties requires precise sequencing and synchronisation across the development phases of the construction project. Thus, the construction supply chain is, in general, extremely complex, especially in large projects, given the high number of organizations involved (R. Zhang & Li, 2011).

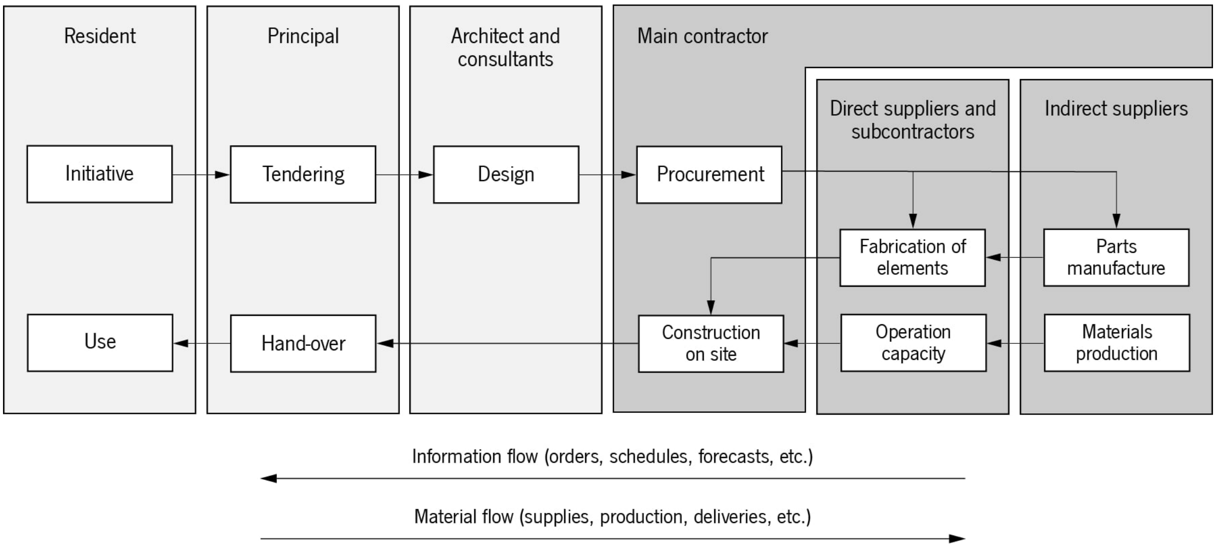

Figure 11. Typical configuration of a traditional construction supply chain.

(Vrijhoef & Koskela, 2000)

In a different perspective, the construction supply chain can be divided into three types: the primary supply chain, which transports the components used to create the finished construction product; the support chain, which offers tools, knowledge, and supplies to speed up building; and the human resource supply chain, which deals with the labour supply (R. Zhang & Li, 2011).

These three chains have a substantial impact on how the supply chain is orchestrated and implemented, giving the SCM processes a high level of complexity. In terms of its structure and functions, according to the literature, the onsite construction supply chain is distinguished by the following elements:

- Convergent supply, sending all resources to the construction site, where the building is assembled;
- Temporary configuration, producing unique projects that entail constant reconfiguration and fragmentation of the supply chain;
- Make-to-order supply, in which each order gives rise to a unique product;
- Contract management as a way of managing relations between organizations involved in the project;
- Activities based on reactive, competitive, unidirectional and short-term oriented information transfer;
- Involvement of hundreds of companies in larger projects to supply materials, components, and a wide range of construction services (R. Zhang & Li, 2011).

Along with these elements, meeting the construction demand is sometimes challenging due to the various delay factors that introduce uncertainty into the process, including human error, equipment failure, and weather conditions, in addition to the difficulty of hiring skilled work force (Gündüz et al., 2013).

Thus, SCM is seen as a critical component in raising competitiveness in a market with increasingly complex requirements. Adapting conventional methods and researching and developing construction alternatives that may decrease the construction complexity and effort are also essential (Vrijhoef & Koskela, 2000).

In this sense, it is argued that **industrialized construction supply chains** are accountable for increasing commercial ties with suppliers as a result of increased integration, as has happened in other sectors that explore modularization strategies (Doran & Giannakis, 2011).

However, as was already noted, the MiC projects SCM faces various challenges. In particular, from the perspective of site supply, production must be set up to ensure the ideal quantity of modules and to prevent waste after the project is finished. This is necessary due to the nature and effort of the modules' production as well as the fact that they are frequently designed for use in unique projects. In other words, the total quantity produced should match the project demand. As a result, from the perspective of stock management, inventory should be zero at the end of the project, as opposed to typical manufacturing supply chains, in which a safety stock must be preserved (Wuni & Shen, 2022f).

Additionally, unlike the onsite construction paradigm, a significant portion of the components are transferred to the manufacturing facilities to be assembled into the modules, which are then delivered to the construction site. Due to the size and requirements of the modules, this transport requires extreme caution and careful management of the capacity of the existing infrastructure and transport equipment (Sharafi et al., 2018). In addition, construction sites generally have limited space, requiring temporary storage sites (Li et al., 2014a). In this regard, the logistics of material supply and resource management are crucial for the success of the industrialized construction paradigm.

When this is taken into account and the schemes in Figures 2 and 11 are compared, it is clear that the supply chain of MiC projects is different from the conventional approach in terms of configuration when it comes to the delivery of materials by suppliers and the transportation of components to the construction site. The new construction paradigm requires separating the materials and equipment needed in the site preparation for installing the modules from those that must supply offsite production, whereas in the traditional approach, all materials and components are shipped directly to the construction site. In addiction, between the conclusion of the manufacturing process at the production plant and the assembly of the modules onsite, transport and possibly storage are required.

Thus, in order to meet the increasingly complex architectural needs of modular customers, there is a clear need for industrialized construction synchronisation and supplier integration. Furthermore, it is concluded that the alignment between modularity and greater degrees of supply chain integration is particularly important as modular product architecture evolves in the construction industry (Doran & Giannakis, 2011).

Therefore, the offsite construction supply chain must be properly configured, synchronised and managed in order to continuously improve production efficiency, coordination and integration of all processes.

2.3.3 Supply chain performance evaluation

The starting point for understanding the importance of evaluating the performance of a process is the premise that “you cannot manage what you cannot measure” (Chan & Qi, 2003).

Traditionally, performance measurement is defined as the quantification of the effectiveness and efficiency of an action. In this sense, a performance measure emerges as a metric for quantifying the effectiveness and/or efficiency of that same action, which should be realistic, representative, consistent, effective, and perceptible. However, no single measure can provide a clear performance goal or focus attention on critical areas of the business. Thus, performance measurement systems that integrate a set of metrics used to quantify and balance the various perspectives that influence the efficiency and effectiveness of the action emerge (Griffis et al., 2007; Kaplan & Norton, 1992; Neely et al., 1995). In this context, a performance metric can be used to evaluate a system or to compare it to competing alternatives. Thus, performance measures can also be employed to build new systems by discovering the decision variable values that deliver the desired performance level(s) (Beamon, 1998).

In modern business management, performance measurement plays a much more significant role than quantification and accounting. It offers crucial data to control performance, reveal progress, improve motivation and communication, and diagnose problems inherent to the process (Chan & Qi, 2003).

From the SCM perspective, performance measurement can aid in supply chain integration while revealing the effectiveness and efficiency of strategies and, consequently, prospects for success. In this context, effectiveness refers to the level of satisfaction of customer requirements, whereas efficiency measures how a company manages its resources to reach a certain level of satisfaction (Neely et al., 1995).

In this regard, suitable and precise performance measures are crucial for SCM. Through these metrics, it is possible to measure the network state and evaluate options during decision-making, ensuring the continuous improvement of supply chain processes and defining directions for future organizational strategies (Kuwaiti & Kay, 2000; Carvalho, 2012). In fact, given the volume of information involved in decision-making, the selection of relevant performance measures is fundamental for the effective management of logistics activity, aiming at the right level of operation and the intended performance (Griffis et al., 2007).

However, since the SCM vision differs from company to company, it is important to base the selection of performance measures on the strategic goals of each supply chain (Carvalho, 2012). Moreover, a wide range of performance metrics are specified in the literature for evaluating the production, distribution, and inventory management processes in supply chains. Thus, the number of possibilities and the complexity of the systems make selecting performance measures challenging (Beamon, 1999).

Additionally, several ways of categorising performance measures within SCM have also been defined. In 1996, Beamon presented some characteristics found in effective performance measurement systems that, thus, could be used to assess the performance of such systems. Beamon (1998) divided the measures defined in the literature – customer satisfaction, responsiveness, flexibility, supplier performance, and costs – into quantitative and qualitative measures. Subsequently, Beamon (1999) identified three categories of measures related to resources, outputs, and process flexibility. Neely et al. (1995), on the other hand, presented four categories of performance measures: quality, time, flexibility, and cost. Furthermore, Gunasekaran et al. (2001) created a system for measuring performance that is based on the strategic, tactical, and operational levels of the supply chain. This method broadly includes operations relating to supply, delivery, customer service and inventory and logistics costs.

According to the numerous perspectives explored in the literature, internal and external performance issues, along with the financial and non-financial components of processes, should be taken into account in order to successfully contribute to crucial decision-making and provide integrated supply chain management. In this way, it is possible to define action plans and redefine objectives and management strategies to achieve the desired performance levels (Chan & Qi, 2003; Neely et al., 1995).

The creation of measuring and evaluation systems that incorporate proper metrics is thus one of the most challenging aspects of choosing performance measures (Beamon, 1999). Combining the many perspectives on supply chain performance measurement discussed in the literature (Beamon, 1996; Chan & Qi, 2003), performance measurement systems ought to:

- be consistent with the organization's objectives;
- be connected with the SCM strategy;
- convey the context of the supply chain;
- ensure a global view of the supply chain;
- be inclusive, allowing measurement of all relevant aspects of the object of study;
- ensure an approach that integrates and balances financial and non-financial measures;
- enable comparison of performance under different operating conditions.

The development of performance measurement systems should also address issues such as what should be measured, how to incorporate different individual measures into a measurement system, how frequently the defined metrics should be measured, how and when they should be reassessed (Beamon, 1999), and what the benefits of this measurement are (Neely et al., 1995).

Although performance measures should be adjusted to the vision of each organization and to the measurement objective, several frameworks have been developed. The next section delves into the performance evaluation models that are most typically used for assessing industrialized construction projects.

2.3.4 Industrialized Construction supply chain performance evaluation

Literature on performance evaluation in the construction industry have shown a current trend of performance improvement moving from the management to the governance level. Traditionally, construction projects have three key goals: cost, time, and quality. This "iron triangle" designates the three criteria for a successful project. Recently, diversified methods of assessing project performance have been proposed. In this sense, the Key Performance Indicator (KPI) approach and maturity models are most frequently employed from a corporate perspective, whilst the Balanced Scorecard and the European Foundation for Quality Management (EFQM) models are embraced from a business standpoint (Wang et al., 2020).

Table 7 lists some of the project performance assessment ideas that have been applied to the modern construction sector. Construction project performance indicators have gradually transitioned from single, static, and stage-based to multidimensional, dynamic, and life cycle, proving the recent trend on performance improvement moving from the management level to the governance level (Wang et al., 2020).

Table 7. Project performance assessment theory in industrialized construction projects.

(Wang et al. (2020))

Assessment theory		**Evaluation Dimension**	**Attributes**
Traditional theory	Financial evaluation	Invest Return Rate, Cost-Effective Ratio, etc.	Static, Single Dimensional, Stage
	Iron triangle	Cost, Quality, Schedule	Static, Multi-Dimensional, Stage
Modern theory	Balanced Scorecard	Finance, Customer, Internal Processes, Innovative Learning	Dynamic, Multi-Dimensional, Stage
	KPI	Finance, Operations, Organization	Dynamic, Multi-Dimensional
	Criteria for performance excellence	Leadership, Strategy, Customer and Market Measurement, Analytical and Knowledge Management, Human Resources, Process Management, Business Results	Dynamic, Multi-Dimensional
	Maturity model	Capability Maturity Level	Dynamic, Multi-Dimensional

In the context of this project, it was deemed appropriate to investigate the Supply Chain Operations Reference (SCOR) model in addition to the modern theory models, based on the research issues and the purpose of evaluating the performance of industrialized building supply chains from several perspectives. Additionally, the Balanced Scorecard model was favoured over the KPI approach from an organizational standpoint because it offers a more thorough review, as seen by the evaluation dimensions included.

Thus, the review on performance evaluation was restricted to a limited set of widely recognised and accepted models: (1) Balanced Scorecard, (2) SCOR, (3) Maturity Models, and (4) EFQM Excellence Model.

Note that although the EFQM Excellence Model was not explicitly created to measure supply chains, it can be adapted to evaluate and enhance construction supply chain performance, as mentioned.

Balanced Scorecard

The Balanced Scorecard was created by Kaplan and Norton (1992) with the idea that a company's performance cannot be evaluated just in terms of financial indicators. In this sense, the authors believe that a balance between four different views should be used to evaluate the supply chain performance. In this regard, in addition to the **financial** aspect, **customer**, **internal business**, and **innovation and learning** perspectives must therefore be assessed. Thus, the supply chain is visualised in a balanced approach since the first two perspectives – customers and shareholders – focus on the short-term vision while the latter two – people and processes – build a picture of the future. Figure 12 depicts the general structure of the Balanced Scorecard approach and the interactions between the perspectives defined by the authors.

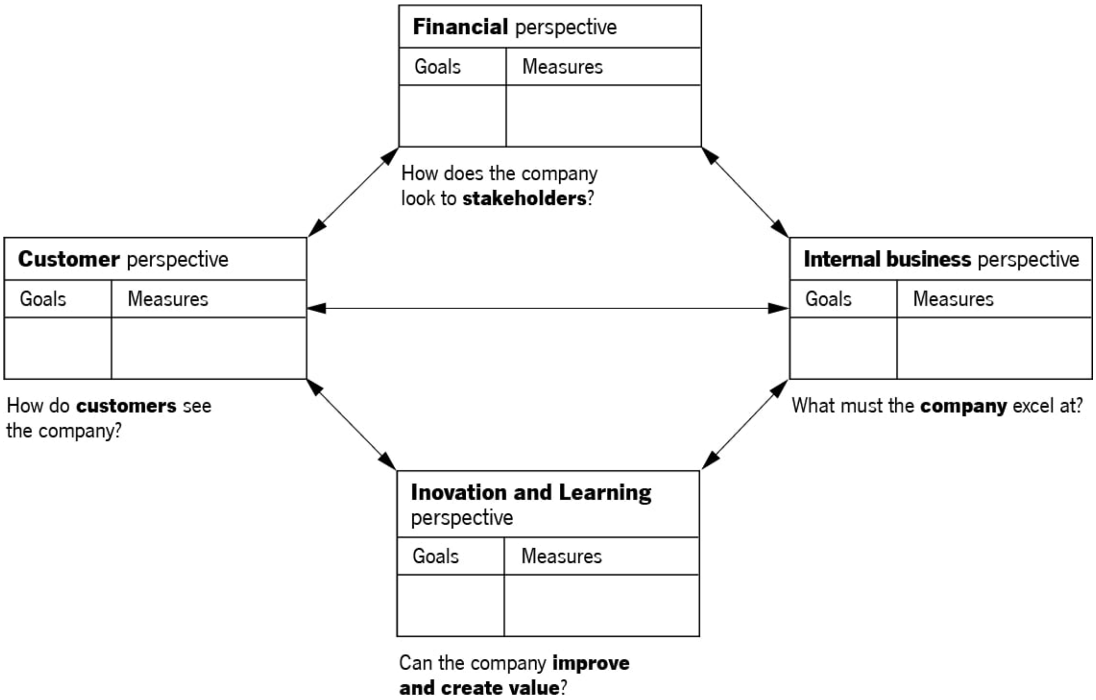

Figure 12. General structure of the Balanced Scorecard approach.
(Kaplan & Norton, 1992)

However, although this is the original framework of the system, several authors have tried to improve the model, including other business aspects that require SCM attention, in order to adjust the approach to the organizations' context. Figure 13 illustrates an adaptation of the Balanced Scorecard model presented by Richards and Grinsted (2020) and developed by *Performetrix*, a software production company. As noted, the environmental perspective is added to the people quadrant.

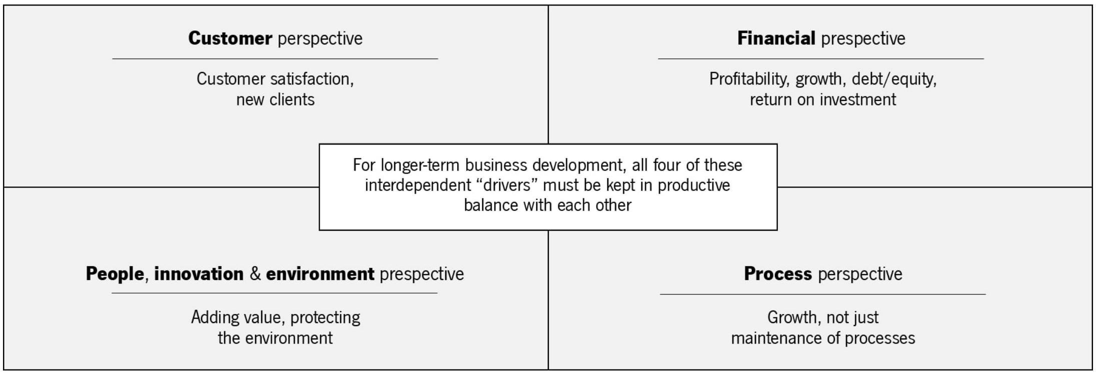

Figure 13. Adaptation of Balanced Scorecard.

(Richards & Grinsted, 2020)

Consequently, the Balanced Scorecard is now a strategic planning tool used in SCM rather than merely a straightforward performance evaluation model. Therefore, in order to implement a balanced scorecard approach, it is necessary to first identify the vision and the strategy for achieving the objectives before defining the activities and performance metrics. On this basis, it should be possible to analyse the supply chain of the organization's strengths and weaknesses, risks and opportunities, and general perception of all balanced perspectives (Richards & Grinsted, 2020). For the application of this method, the following steps can be defined:

1. Confirm/review the organization's vision;
2. Formulate overall strategic objectives;
3. Identify critical factors and define initial performance indicators, ensuring that they are specific, measurable, achievable, relevant and with a defined time horizon;
4. Create metrics for performance indicators – each measure should have associated objectives and targets, measured against actual performance;
5. Review the measures to ensure that they offer a balanced perspective.;
6. Establish an overarching framework;
7. Translating vision into strategy and strategy into daily action;
8. Define short- and long-term objectives;
9. Develop an action plan to achieve those objectives;
10. Ensure continuous monitoring of performance evaluation (Richards & Grinsted, 2020).

Supply Chain Operations Reference (SCOR)

The SCOR model explains the business activities connected with meeting consumer demand, by monitoring and comparing supply chain operations and their performance. It was created in 1996 by Association for Supply Chain Management (ASCM), a merging of the former APICS and the Supply Chain Council, and has since been constantly updated to reflect the ongoing growth of supply chain business practices. The most recent version (v14.0), on which this review is based, refers to 2022 (ASCM, 2022).

Currently, it represents a consensual vision of SCM, providing a unique framework that connects business processes, metrics, practices, and technology in a structure that supports communication among supply chain actors. Thus, it enables the improvement of SCM effectiveness, which directly affects operational performance (ASCM, 2022; Supply Chain Council, 2017).

As a process reference model, the aim of SCOR is to define a process performance architecture that is in line with the major business functions and objectives. In this way, it aims to establish how processes are configured, executed, and interact with each other, as well as the competence requirements for the personnel operating them (ASCM, 2022). In this sense, the structure of the model can be divided into four main elements, which are explored in this subsection:

- Processes – provides common definitions of management processes and their connections;
- Performance – offers standard metrics to describe process performance and define strategic goals;
- Practices – describes the management practices that lead to improved process performance;
- People – contains definitions that are commonly used for the skills required to perform supply chain processes (ASCM, 2022).

The **Processes** section of the model provides a set of predefined descriptions of the processes that most companies undertake to operate their supply chains effectively. Thus, the structure of the model is organised into seven major management processes, presented in Table 8 and schematised in Figure 14.

Due to this categorisation, the model can explain very simple or extremely complicated supply chains using a common set of criteria. The official representation of the seven major SCOR processes, uses a double infinite diagram to illustrate how they interact with one another. The purpose of this depiction is to schematise the connections and continuous nature of the supply chain essential processes. In this approach, the model's structure displays a balance between *Supply* and *Demand* in an infinite horizontal loop and between *Synchronise* and *Regenerate* in an infinite vertical loop (ASCM, 2022).

Table 8. Description of the SCOR major management processes.

(ASCM, 2022)

Process	**Description**
Orchestrate	Activities relating to the integration and implementation of SCM strategies. Focuses on the main processes necessary to connect the supply chain externally (suppliers and consumers) as well as to internal stakeholders.
Plan	Activities related to creating supply chain operation plans, considering the Order, Source, Transform, Fulfil, and Return processes. These include evaluating requirements, acquiring information about available resources, balancing requirements and resources to evaluate planned capabilities and gaps in demand or resources, and recommending steps to close these gaps.
Order	Activities related to the customer purchase of products or services, including information about locations, payment methods, prices, fulfilment status, and any other order data.
Source	Activities associated with acquiring, ordering, scheduling, delivering, receiving, and transferring products and/or services.
Transform	Production, assembly/disassembly, maintenance, repair, and other related activities that go into producing products and services.
Fulfill	Activities related to fulfilling customer product orders, including scheduling order delivery, picking, packing, shipping, assembling, installing, commissioning, and invoicing.
Return	Activities related to the reverse flow of products, services, and/or any service components from a customer back through a supply/service chain to diagnose condition, assess entitlement, dispose back into Transform or other circular activities, and pre-position inventory or service.

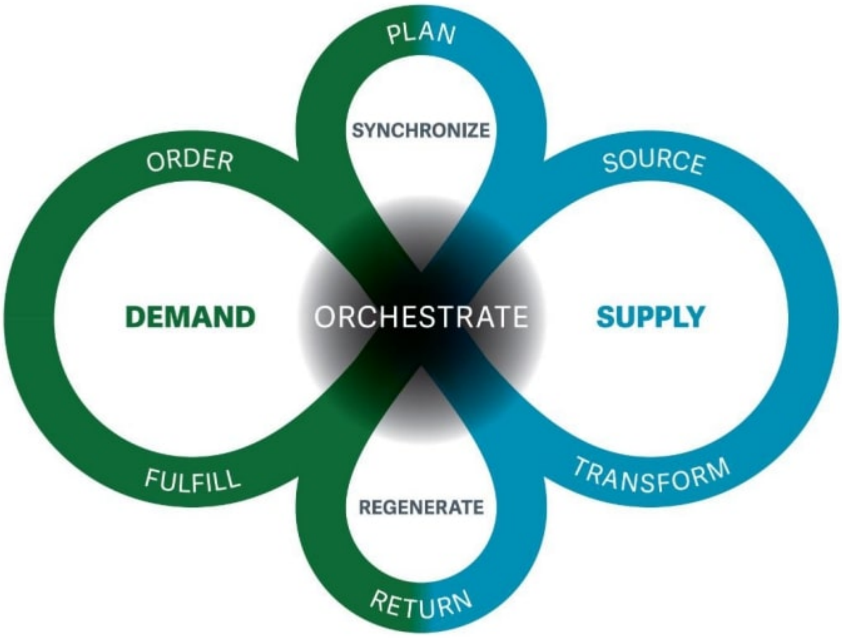

Figure 14. SCOR seven major management processes.

(ASCM, 2022)

The model thus encompasses all customer interactions from order placement to invoice payment, all physical material transactions from primary suppliers to ultimate consumers, and all market interactions from identifying overall demand to fulfilling every order. The model is built to support the supply chain at multiple levels in order to manage all transactions effectively, as shown in Figure 15.

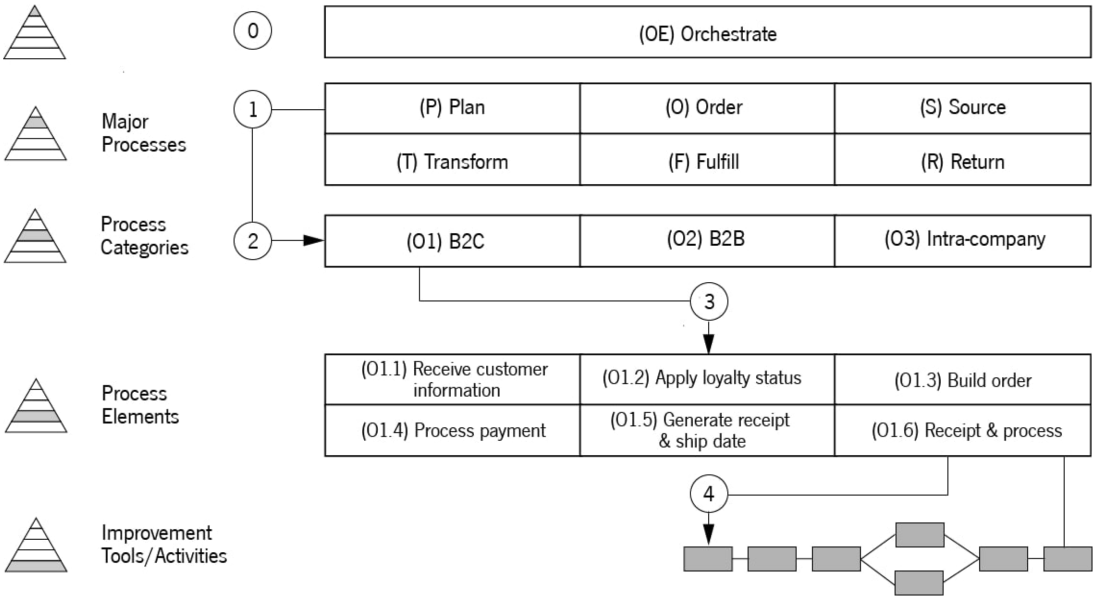

Figure 15. SCOR hierarchical structure – *Order* process example.

(ASCM, 2022)

As noted, SCOR identifies that the *Orchestrate* process belongs to Level 0 of the SCOR hierarchy structure among the major macroprocesses. *Plan, Order, Source, Transform, Fulfil,* and *Return* are the six Level 1 processes that define the essential operations and outline the scope, content, and performance goals of the supply chain. The operations strategy and process capabilities are specified by Level 2 processes, which represent the macro categories found in Level 0 and 1 processes. Level 3 is concerned with process elements, defining execution capacity for individual processes while concentrating on processes, competencies, performance, practices, and capabilities. In this way, the model focuses on Levels 0 to 3 as neutral processes applicable to any industry. Each organization should implement supply chain improvement actions to develop the model to Level 4 through industry, organization, and site specific processes, systems, and practices (e.g. Kaizen, Lean, Total Quality Management (TQM), Six Sigma, benchmarking) in order to allow for the model's adaptation to each business' unique systems and flows (ASCM, 2022).

In turn, the **Performance** section of SCOR focuses on comprehending supply chain outcomes and consists of two elements: performance attributes and metrics. A performance attribute is a set of strategic characteristics used to align supply chain performance with the organization's strategy. Since an attribute itself cannot be measured but is only used for setting a strategic direction, it is expressed through metrics, which are discrete measures of process performance (Supply Chain Council, 2017). In this context, SCOR recognises three performance categories that include eight attributes, as shown in Table 9. The model assigns precise performance metrics to each attribute. It is worth noting that the resilience attributes are customer-focused, whereas the economic category is concerned with internal supply chain attributes. The sustainability category, on the other hand, guarantees that external factors are considered (ASCM, 2022).

Table 9. Description of the SCOR performance attributes.

(ASCM, 2022)

Performance category	**Performance attribute**	**Description**
Resilience	Reliability	The ability to perform tasks as expected, focusing on process outcome predictability. Metrics for the Reliability attribute commonly include delivering a product on schedule, in the right quantity, and at the right quality level.
	Responsiveness	The rate at which tasks are completed and the rate at which a supply chain delivers products/services to customers. Includes cycle-time metrics.
	Agility	The ability to react to external factors and market changes in order to obtain or keep a competitive advantage.
Economic	Costs	The cost of operating the supply chain processes. This covers labour, material, managerial, and transportation costs.
	Profit	The financial benefit experienced when the income from a commercial activity outweighs the costs, costs, and taxes incurred to maintain the activity.
	Assets	The ability to use assets effectively. Inventory reduction and internal sourcing, as opposed to outsourcing, are asset strategies in a supply chain.
Sustainability	Environmental	The ability to manage the supply chain with minimum environmental impact (materials, water, and energy).
	Social	The ability to manage a supply chain that is consistent with the organization social values, such as diversity and inclusion, salary and training measures.

A **SCOR Practice** is a unique way of configuring a process or set of processes based on the level of automation and technology, the skills required, and the sequence of execution. Each practice is related to one or more basic processes, performance metrics or competencies, and are transversal to the type of industry, configuring four base pillars: analytical, technology, process, and organization. In this context, the practices are mapped to one or more pillars in order to identify the pillar on which each practise has the most influence and provides the greatest advantage (Supply Chain Council, 2017).

Finally, the **People** section of SCOR aims to provide a way of managing talent in the supply chain by describing the competencies needed to execute and manage the processes. According to the SCOR model, a competence is the ability to achieve specified results with the least amount of time and effort. In this manner, this last section supplements the others by aligning individuals and their competencies with these model features (Supply Chain Council, 2017).

Maturity Models

Adaptable, effective, and mature supply chains help companies remain competitive while increasing value for customers and shareholders. Thus, the maturity level of a company's supply chain must be monitored and continuously improved to ensure its competitive market positioning (Lahti et al., 2009).

In this context, maturity models have emerged as a tool for evaluation and improvement that integrate the concepts of process maturity and capacity and are increasingly being applied to the multiple dimensions of logistics and the supply chain. In fact, in this field, some organizations have a long way to go in terms of SCM while others have advanced tremendously in the last few decades (Richards & Grinsted, 2020).

The word maturity literally means"ripeness", which conveys the sense of development from an early stage to a later stage. This is based on the evolutionary theory, which contends that the subject may pass through a number of intermediate states before reaching maturity (Lahti et al., 2009). Thus, performance evaluation based on maturity models aids in the decision-making process regarding the measures required to improve performance, allowing for the formulation of an implementation strategy. In other words, in addition to identifying the company's current development stage (or "maturity") this instrument helps the definition of the next steps towards advanced practices (Lahti et al., 2009; Richards & Grinsted, 2020).

Typically, maturity is described in four or five levels, ranging from low to high performance, but any number of levels can be included. For example, given the evolution of manufacturing's strategic importance, a four-stage maturity model for the logistics and supply chain function can be established, from an "internally neutral" to a "externally supportive" level. From this point of view, at the first level of contribution to the business, the manufacturing function is reactive and requires outside aid to make strategic decisions. Looking outside the firm, it can implement industry best practices and improve its performance and become "externally neutral". Then, by developing and supporting the implementation of a manufacturing strategy, it is possible to attain the "internally supportive" level. Finally, the highest level is reached when manufacturing has a level of process and technology innovation that makes it participate in crucial engineering and marketing decisions (Richards & Grinsted, 2020). This connection between performance improvement and maturity level is schematised in Figure 16.

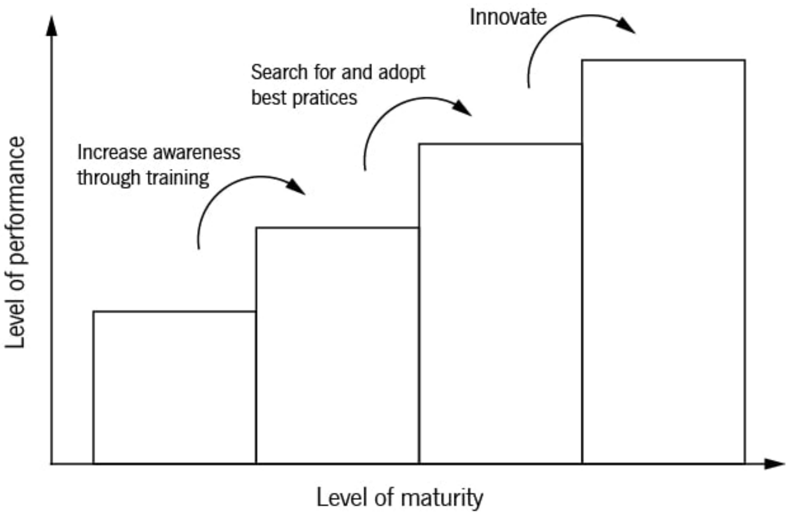

Figure 16. Link between improving performance and maturity.
(Richards & Grinsted, 2020)

Maturity assessment therefore assumes that processes are well-accepted, backed by training and documentation, utilised in projects consistently across the company, and regularly monitored and improved by people who execute them (Lahti et al., 2009).

Although maturity models have been developed for a wide range of objectives and activities, the concept originated from the software manufacturing industry, with the Capability Maturity Model (CMM). This model has been utilised by many organizations to identify the best practices fit to raise the maturity of processes. In order to achieve increasingly higher degrees of maturity, the CMM states that a cumulative list of essential process areas should be developed and fulfilled. In this manner, the CMM is a fundamental and widely used technique for measuring project management performance. Several maturity models from other domains have been presented, and Table 10 lists the most frequent maturity models along with their basic information. It is argued that the CMM based the majority of the standard maturity models, and both quantitative and qualitative analyses were used to implement the maturity evaluation. The most typical maturity area is project management maturity (Wang et al., 2020).

Table 10. Common maturity models with their characteristics.

(Wang et al., 2020)

Maturity model	**Number of levels**	**Application area**	**CMM-based**	**Quantitative analysis**	**Qualitative analysis**
Capability Maturity Model Integrated	5	Software industry	✓	✓	✓
Construction Industry Macro Maturity Model	4	Construction industry	✓	✓	✓
Organizational Project Management Maturity Model	3	Project management	✓	✓	
Berkley Project Management Process Maturity Model	4	Project management	✓	✓	
Portfolio, Programme and Project Management Maturiry	5	Project management	✓	✓	✓
Standardized Process Improvement for Construction Enterprises	5	Construction industry	✓	✓	✓
Change Management Maturity Model	5	Construction industry	✓	✓	✓
Maturity Assessment Grid from the Strategic Forum for Construction	5	Construction industry		✓	
Project Management Maturity Model	5	Project management	✓	✓	✓
Kerzner Project Management Maturiry Model	5	Project management	✓	✓	✓

In the construction industry, many maturity models have been developed to facilitate project management tasks involving BIM, information and risk management, construction SCM, construction safety, and detailed engineering maturity (Wang et al., 2020). In addition to the models listed by Wang et al. (2020), from the perspective of the construction supply chain, Vaidyanathan and Howell (2007) have proposed the Construction Supply Chain Maturity Model (CSCMM). The objective of this model is to provide a plan to achieve operational excellence, so that a construction project can benefit from increased overall performance (Lahti et al., 2009). In fact, all existing construction management assessment methodologies have demonstrated that the maturity model is capable of revealing shortcomings and indicating stages of performance growth that assist managers in efficiently achieving project objectives (Wang et al., 2020).

With regard to CI, Wang et al. (2020) define maturity as the "the project organization's capability to successfully achieve predetermined project goals by adopting industrialized construction technology and corresponding management approach". However, little research has been done already to investigate industrialized construction maturity evaluation. There have been some experiments on identifying the industrialized construction mode and evaluating the state of its applications. The vast majority of studies in this field have only identified areas of process and outcome weakness; they haven't succeeded in making concrete recommendations for how to improve the industrialized construction project performance, and the indicators currently used in the evaluation system hardly take organizational enablers into account. In order to close the research gap of the industrialized construction maturity evaluation approach, Wang et al. (2020) attempted to incorporate obstacles and critical factors, a maturity model framework, and the organizational enablers theory, combining maturity assessment with the EFQM Excellence Model.

EFQM Excellence Model

Based on the TQM principles, the EFQM Excellence Model was created as a quality management system by EFQM in 1991. Its primary goal is to evaluate the level of organizational excellence of a company by identifying performance deviations compared to the best practices adopted in the sector and to help define improvement actions (Vukomanovic et al., 2014). As a result, the model offers organizations with a tool for self-assessment and performance improvement.

This tool assesses performance against nine criteria and 32 associated sub-criteria, which are weighted based on the impact of the performance category on the overall assessment. The model configuration and the weights defined by the authors (shown in brackets in each criteria box) are depicted in Figure 17. Furthermore, the model distinguishes between process indicators (known as leading indicators) and result indicators (lagging indicators). Thus, the model's structure is divided into two parts: enablers and results. Enablers describe what the company should do to meet its mission and achieve the set of objectives. Originally, five dimensions of enablers were examined in the EFQM model – "leadership", "people", "strategy", "partnerships and resources" and "processes". Project performance results, on the other hand, are concerned with determining what is relevant from the standpoint of stakeholders (lagging indicators). In this sense, the model defines four dimensions of results, which are related with "people," "customer", "society", and "business", respectively. Thus, in terms of measured dimensions, the EFQM model includes organizational enablers (how) and performance outcomes (what), which are used to assess success and measure and improve project performance (Vukomanovic et al., 2014; Wang et al., 2020).

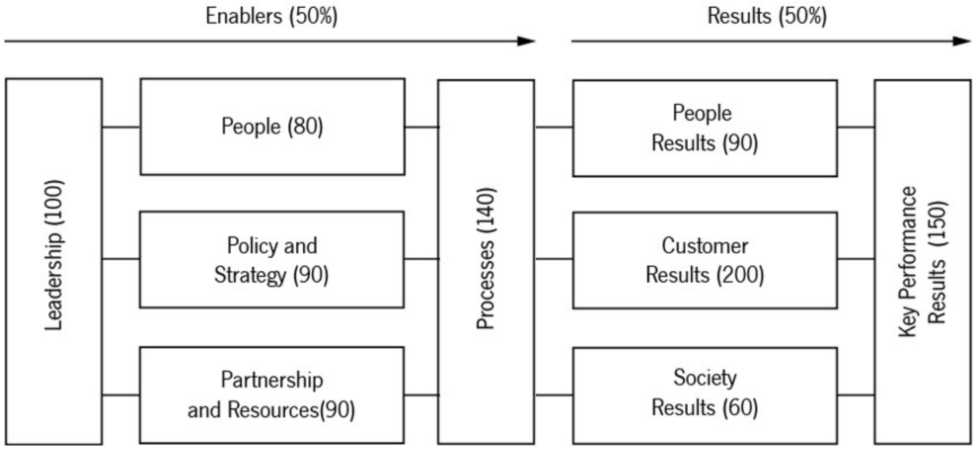

Figure 17. EFQM Excellence Model.

(Vukomanovic et al., 2014)

The EFQM model is frequently used in the construction industry. However, it is necessary to adapt this quality management tool to the context of the construction activity. In this regard, Vukomanovic et al. (2014) devised an assessment system that blends the EFQM model with the Balanced Scorecard approach to construction company strategic control. The authors' approach was validated in a case study involving over 30 construction enterprises in South East Europe. On the other hand, the EFQM model's usefulness for assessing the maturity of construction projects was demonstrated, particularly through the performance improvement help offered by the designation of organizational enablers (Wang et al., 2020).

Indeed, in the literature has been demonstrated that the EFQM model, as a method of achieving "business excellence" plays an important role in improving the performance of building projects (Wang et al., 2020).

2.4 Literature review synthesis

The purpose of this review was to offer an overview of the most important literature findings to support the research in achieving the main objectives.

When taking the development environment into account, it is crucial to note that "Construction industrialization", which refers to the application of production management principles and methods to the AEC industry, evolved to address the difficulties of construction projects. To realize its full potential, it demands the standardization and modularization of components, the streamlining of processes, and the optimal use of resources. This transition process is based on lean transformation, innovative manufacturing techniques, and improved supply chain orchestration. As a result, construction projects can be developed based on the assembly of 80 to 90% of building units in a factory away from the construction site, forming one of the most explored offsite construction systems that have emerged in recent years – MiC.

This innovative construction paradigm relies on modularity and modularization principles that have already been explored in other industries to improve the stages of the construction process and address the "Benefits and challenges of Modular Integrated Construction Projects", such as reduced construction time, cost savings, improved quality, safety, and project sustainability, project planning complexity, and logistics coordination. To deal with them, it is vital to look at the Critical factors of modular construction projects that can be scattered throughout many categories, such as project requirements, culture and leadership, process planning and control, supply chain coordination, process efficiency, time, cost, quality, safety, and environmental sustainability.

Furthermore, because modularity and different levels of modularization involve the decomposition of the product architecture, DSM emerges as a recognized technique used in product architecture for breaking down and depicting relationships between product components, which can thus be used to cluster product components into modules with minimal external interfaces and maximum internal integration between components. Although there is a literature gap about the application of this technique in the construction industry, in accordance with the findings of AlGeddawy and ElMaraghy (2013), it is concluded that the construction of levels of modularization can rely on the identification of the optimum granularity level and number of modules based on hierarchical clustering to construct a product hierarchical architecture from DSM and minimum MI determination.

When determining the optimal level of modularization based on the performance of the related supply chain, it is critical to remember that a "Supply chain" is a network of organizations involved in activities that create value for the customer in the form of products and services via upstream and downstream links, encompassing materials, information, and resource flows. Participants in the construction supply chain are involved in project planning, contract administration, procurement of services and materials, and manufacture and delivery of materials to the construction site. Furthermore, when comparing "Conventional vs. industrialized construction supply chain", disparities in lead times, inventory management, and transportation logistics are revealed, as shown by the benefits, challenges, and critical factors of MiC projects. Moreover, it is critical to remember the significance of analyzing process performance in order to optimize processes and achieve project objectives. In this regard, the most commonly used "Supply chain performance evaluation" methods for assessing industrialized construction projects are Balanced Scorecards, SCOR, Maturity Models, and the EFQM Excellence Model, which will serve as the foundation for the development of the proposed framework.

3 Conceptual framework

In this chapter, a framework is proposed to assist construction project designers in deciding the right level of modularization for a given project based on the performance of the supply chain involved.

First, the framework establishment is explained, emphasising how the SLR on MiC projects' critical factors and the NLR on supply chain performance evaluation methods served as the foundation for defining the framework structure and factor inclusion. Then, it is described how the results of the semi-structured interviews were used to validate and optimise the literature-based framework. Afterwards, the proposed framework structure is presented and dissected in light of the defined implementation steps.

3.1 Research methodology

The methods in this research involved the establishment and validation of a conceptual framework.

The framework establishment was implemented as the following three steps: (1) designing different levels of modularization within a construction project, (2) diagnosing the system's CI capability, and (3) setting a performance evaluation system. First, designing different levels of modularization within a construction project: in order to fill the research gap on decomposing construction projects using product architecture and DSM concepts in the construction industry, the approach proposed by AlGeddawy and ElMaraghy (2013) is suggested to be included in the framework to aid in the design of different levels of modularization whose performance should be compared to define the most appropriate one for the construction project. Second, diagnosing the system's CI capability: the system's evaluation factors were defined based on the SLR. The foremost objective is to guide the decision-making process on the ideal level of modularization, considering the critical factors affecting MiC project implementation and assisting in capturing the current organizational culture, expertise, and industrialization capability. Third, setting a performance evaluation system: the supply chain performance evaluation approach was defined by applying the literature findings on various supply chain performance evaluation methods. As a foundation, the evaluation indicators use SLR on critical factors and the review of SCOR metrics. To design the framework evaluation structure, the SLR factor categories, revealed in section 2.2, were logically arranged in accordance with the structure of established evaluation methods (EFQM Excellence Model, Balanced Scorecard, and SCOR).

To validate the literature-based framework, face-to-face semi-structured interviews were undertaken. The interviewees were 11 experts with extensive construction cognition and practical experience, selected based on their role in the MiC implementation project at the company where this research was conducted. All interviewees were provided with information on the research topic and the conceptual framework before the interviews. According to the research elements stated in section 1.3, six interviews — one-element and focus groups[1] — were conducted, considering the interview protocol detailed in Appendix B. Table 11 outlines the interviewees' positions, areas of expertise, and the overall contribution of individual or focus group interviews to this research. Despite the fact that all participants answered broad questions about the project context and framework structure, each interview was tailored to the participants' areas of expertise[2].

Table 11. Interviews' participants and their research contribution.

No.	Position	Area of expertise	Major contributions
1	Head of Modular Construction (HMC)	Project management	Evaluation factors and structure of the project requirements analysis phase; design and decomposition of building modules; time and cost performance evaluation indicators.
2	Head of Project Preparation Officer (HPP)	Architecture	
3	Head of Architecture (HA)	Architecture	
4	Project Manager (ProjM)	Project management	
5	Head of BIM Officer (HBIM)	Modelling technology	Evaluation factors related to modelling technology required to implement MiC projects; time and cost performance evaluation indicators.
6	Production Manager 1 (ProdM1)	Production system	Evaluation factors related to the company's production/construction planning and control capability; time, cost, and process efficiency performance evaluation indicators.
7	Production Manager 2 (ProdM2)	Production system	
8	Construction Team Leader (CTL)	Construction	Evaluation factors related to company's capacity to perform the planned onsite activities; time and cost performance evaluation indicators.
9	Logistics and Supply Chain Manager (LSCM)	Logistics and Supply chain	Evaluation factors related to the company's capability to coordinate logistic activities and the project related supply chain; time, cost, and process efficiency performance evaluation indicators.
10	Quality Manager (QM)	Quality	Quality, safety, and environmental sustainability performance evaluation indicators.
11	Safety Manager (SM)	Safety	

For in-depth analysis, the main conclusions for each question in each interview have been collected. The irrelevant and redundant data was then eliminated, and responses from various participants and groups were compared to detect parallels and variations in opinions. Thus, the results of all interviews were combined to produce more consistent results. Finally, using a triangulation technique, the results were compared to the literature findings and validated by the experts involved, as the revised structure was handed back to them after each interview and a second meeting was organised to confirm it.

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[1] Each interview question was assigned to the expert whose daily job is most closely related to the problem under investigation. The experts who had the exact same questions were placed in a focus group to construct more consistent results, by sharing ideas about it.

[2] ProdM1 is specialised in industrialized production systems, while ProdM2 is in charge of MiC projects' production system implementation.

Thus, the interviews' results enable the improvement of the framework structure and factor inclusion. In terms of structure, the literature-based evaluation dimensions were rearranged into a systematic decision-making process in which distinct decision steps must be individualised into separate framework phases, as exposed in Appendix B. Furthermore, the evaluation factors and indicators were revised from a practical standpoint to fit the theoretical framework to the construction context, as explained in the next section.

3.2 Framework structure

Considering this, in this section, the proposed framework structure, shown in Figure 18, is dissected, considering the three implementation steps: (1) Design of different levels of modularization, (2) System's CI capability diagnosis, and (3) Performance evaluation system.

The D codes used in this section correspond to the categories defined in section 2.2. They are used to emphasise the SLR's contributions to the proposed structure. However, in the framework structure, they were modified to make it more intuitive: Project Requirements, D1, was renamed to PR, D2 to D5 are referred to as E1 to E4, which are the four "enablers" dimensions, and D6 to D11 were dispersed by the four dimensions of "results", which are denoted with the codes R1 to R4.

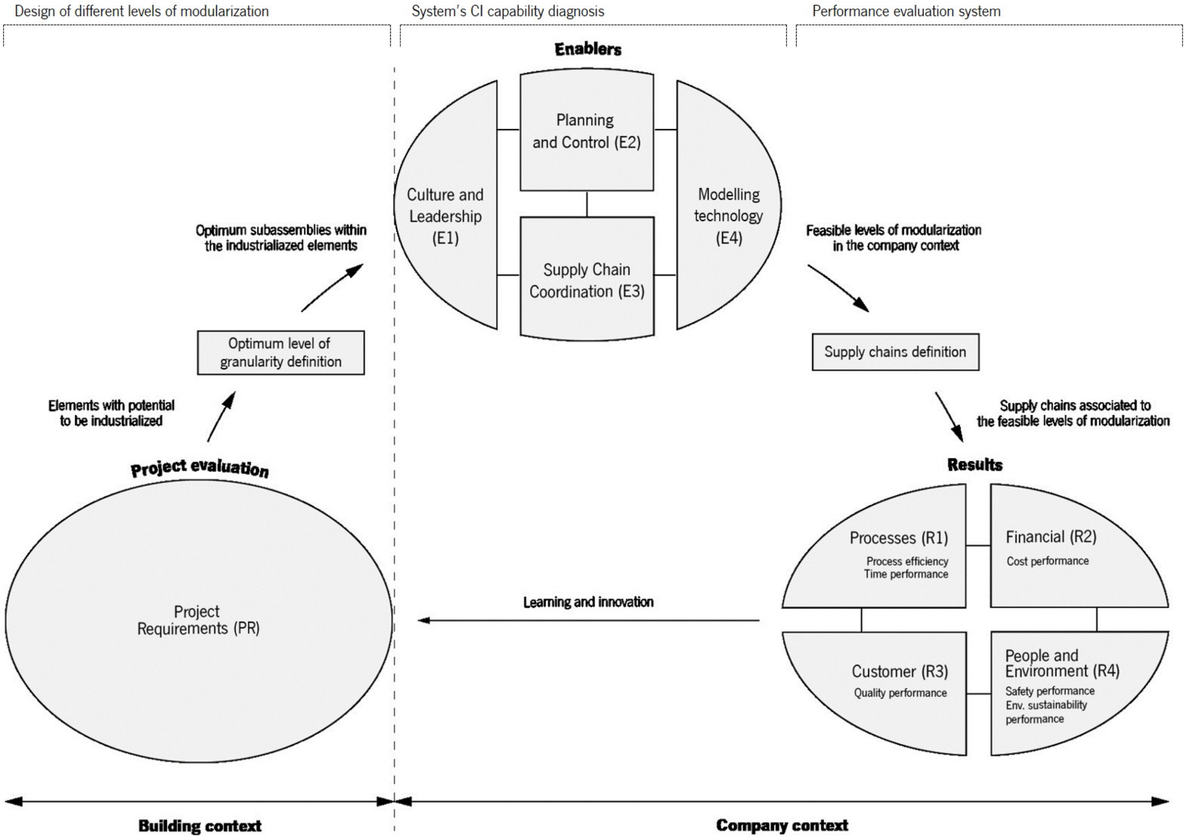

Figure 18. Developed framework structure.

Design of different levels of modularization

First, different modular scenarios must be defined entirely by the architectural context and the required material typology ("Building context"). In other words, it should be assessed whether the project requirements allow for the development of building modules. As a result, a preliminary assessment of the construction project must involve an extensive review of the **Project Requirements** (D1) to determine the project's modular potential, comprising evaluation factors based on the SLR and interviews' results.

Subsequently, the building modules' structure should be decomposed by using the technique presented by AlGeddawy and ElMaraghy (2013), exposed in subsection 2.1.4. It should be noted that, as the ideal level of granularity corresponds to the decomposition level that maximizes internal integration while minimizing interactions between components, by defining the optimum number of sub-modules, a related construction scenario allows the quality optimization of the product modulatiry (AlGeddawy & ElMaraghy, 2013).

System's CI capability diagnosis

Then, considering the "Company's context", the framework support the evaluation of the company's CI capability to develop the sub-modules identified for the optimum level of granularity offsite, based on factors that aid in capturing the current organizational culture, expertise, and industrialization capability. Considering the degree of fulfilment of the different evaluation factors, several scenarios for conducting assembly tasks offsite (corresponding to different levels of modularization) can be considered. If the requirements for the offsite development of those modular scenarios are not met, the framework's second phase evaluation factors must assist in evaluating which areas require investments.

With the NLR on supply chain performance evaluation methods as a foundation, it was decided to base this phase on the EFQM Excellence Model "enablers". Thus, the definition of the feasible levels of modularization is based on the evaluation of four dimensions of "enablers", considering the categories of factors identified in the SLR and the interviews' results. Thus, the "enablers" are **Culture and leadership** (D2), **Planning and control** (D3), **Supply chain coordination** (D4), and **Modelling technology** (D5). Although the entire framework structure has been revised by the interview participants, the established factors for the "Culture and leadership" dimension were only based on reviewed literature because, if generated in the context of a company, findings could be biased by the organizational culture[3].

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[3] The factor "Capacity and experience in CI projects", identified via SLR, was not included because it was not considered to be essential to start exploring modular solutions, although modular history improves the project performance.

Performance evaluation system

Then, it is required to design the most suitable supply chains for the development of the defined feasible levels of modularization, considering industry best practises and the most accurate and beneficial configuration for each modular scenario (keeping E2, E3, and E4 assessment in mind), as these influence the performance results and, therefore, the modular construction strategy employed.

The supply chain performance evaluation relies in four dimensions of "results", also considering the EFQM structure, the SLR, and the interviews' results. Thus, the remaining categories defined on the SLR constitute the "results" dimensions, based on Balanced Scorecards: **Processes**, which comprises Process efficiency (D6) and Time performance (D7), **Financial** that corresponds to Cost performance (D8), **Customer**, including Quality performance (D9), and **People and environment**, which includes Safety (D10) and Environmental sustainability performance (D11). Thus, the assessment considers both a short-term vision that is centred on the needs of the client and the financial interests of the shareholders and a long-term vision that is based on environmental, social, and process efficiency factors.

To support the supply chain performance evaluation, in this framework phase, the indicators based on the SLR findings and conducted interviews[4] were cross-referenced with SCOR metrics from the most recent open access version (v14.0), which refers to 2022[5]. Based on Bullinger et al. (2002) work, it is proposed an integrated measuring system that combines Balanced Scorecards perspectives with SCOR metrics. The consideration of SCOR metrics is justified in the sense of controlling the materials and products flow through the measurement of logistical performance (adapted for supply chain analysis, in this context), while the balanced perspectives allow monitoring the logistics objectives of the project through the management performance measurement, as shown in Figure 19.

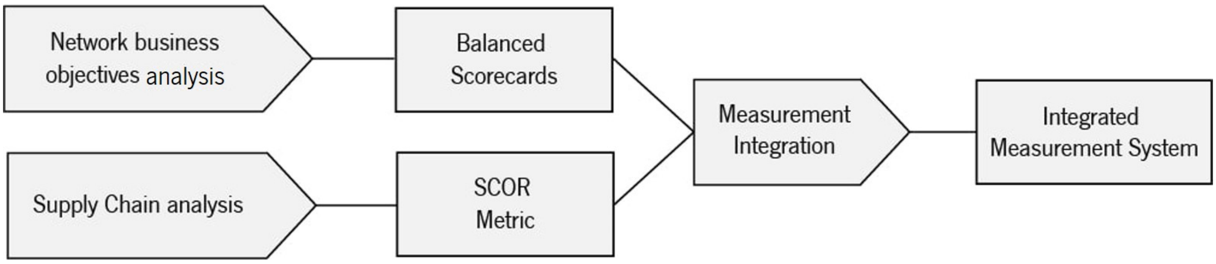

Figure 19. Balanced measurement methodology.

(adapted from Bullinger et al. (2002))

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[4] Only three critical factors identified in the SLR have no correspondence in the proposed metrics because, based on the interviews' results they are not relevant/accessible in the construction project design phase.

[5] The results of this comparison were also validated by the interviews' participants.

Thus, the framework output is a supply chain performance assessment, for each perspective, associated to the viable modular scenarios. There will be as many different outputs as the supply chains built based on the feasible levels of modularization. The project team should then assess these various outcomes to choose the level that leads to the results that best suits the business strategy, objectives and mission.

Considering the proposed framework implementation, Tables 12, 13, and 14 present the evaluation categories of each phase, while Tables 15, 16, and 17 outline the factors and indicators included. The "source" columns identify the foundation of each dimension, factor, or indicator. For the "enablers" evaluation, a summary justification of the relevance of every factor is included, based on the SLR and interview results.

Table 12. Description of "project requirements" dimension.

Code	**Dimension**	**Description**	**Source**
PR	Project Requirements	Preliminary analysis of building requirements to define which elements can be industrialized, by analysing the repeatability of structure's geometry, materials standardization, and assembly interfaces and tolerances.	SLR dimensions Interviews' results

Table 13. Description of the evaluation dimensions in the "enablers" phase.

Code	**Dimension**	**Description**	**Source**
E1	Culture and leadership	It covers the company cognition and attitude towards CI. To promote performance excellence and optimization of CI initiatives, it guarantee the required technical and decision-making support, as well as an adequate communication culture.	EFQM "leadership" SLR dimensions Interviews' results
E2	Planning and control	It entails the management of plant, site, supply, storage, and transportation capacities, as well as constraints to produce modules with the desired dimensions and attributes.	EFQM "processes" SLR dimensions Interviews' results
E3	Supply chain coordination	Established to ensure that the supply chain capability and expertise in CI and the availability of necessary suppliers and management strategies are taken into account to establish viable modular options.	EFQM "partnerships and resources" SLR dimensions Interviews' results
E4	Modelling Technology	It ensures that factors that optimize decision-making in construction information management are considered, to comprehend the viability and compatibility of design and engineering solutions to address the practical challenges of MiC during the design, production, and construction stages. It aids the integrated production system and technical performance.	SLR dimensions Interviews' results

Table 14. Description of the evaluation dimensions in the "results" phase.

Code	**Dimension**	**Description**	**Source**
R1	Processes	Performance of maintenance assessment and improvement processes based on the **transformation** and **order fulfilment agility** and **responsiveness** of the project.	Balanced Scorecard SCOR attributes SLR dimensions Interviews' results
R2	Financial	Assessment of the financial sustainability of the construction project, analysing the **costs** involved in the supply chain.	Balanced Scorecard SCOR attributes SLR dimensions Interviews' results
R3	Customer	The owner of the construction project is considered its "customer". Thus, it aims to assess the degree of compliance with the **reliability** requirements, associated to the supply chain quality performance, promoting customer satisfaction.	EFQM "customer" Balanced Scorecard SCOR attributes SLR dimensions Interviews' results
R4	People and Environment	Consideration of the impact of the construction project on "society", assessing the **social** and **environmental sustainability** of the processes.	EFQM "society" Balanced Scorecard SCOR attributes SLR dimensions Interviews' results

Table 15. Evaluation factors for the “project requirements” assessing phase.

PR	**Project Requirements**		
Code	**Factor**	**Description**	**Source**
PR1	Repeatability	The extent to which isolated components can be seen as independent modular solutions	*SLR D1.6*: Repeatability in design is crucial to benefit from full schedule and cost benefits and to achieve scale [5]. *Interviews' results*: Design, geometry, and compartmentalization repeatability improves economies of scale of large volumes of module production.
PR2	Standardization	The extent to which the construction elements are standardized	*Interviews' results*: It is critical to search for standardized materials, architectural structures, finishes (aesthetics), inter- or intra-module interfaces, and manufacturing procedures for producing the modules under consideration.
PR3	Client's receptivity	Client openness to implement industrialized/modular solutions	*SLR D1.1, D1.2*: It is vital to ensure an early commitment to build design that is compatible with CI principles [6]. Poor client knowledge and receptivity to MiC is a driving factor in late advice and MiC consideration in a project [12]. *Interviews' results*: Client's receptivity can be a critical limitation to the development of a certain modular solution.
PR4	Design flexibility	The extent to which established design features can be altered during the design process to adjust the design to the needs for the industrialization of the building section(s)	*Interviews' results*: When it is necessary to transition a construction project from a conventional to an industrialized paradigm, the client must be willing to accept functional design changes in order to tailor module manufacturing to installation and building integration requirements.
PR5	Design freezing	The extent to which design features are frozen at the planning phase, without the possibility of adjustments during the project execution	*SLR D1.8*: In traditional construction, clients can typically alter design specifications based on contract conditions. The design freeze prevents it and forces clients to accept a finalised design even before modules' production [3].
PR6	Building integration	The extent to which the defined modules can be fully integrated into the building structure	*Interviews' results*: When considering the industrialization of a specific building element, it is necessary to evaluate and develop interface solutions to enable its integration with the building's systems (e.g., Mechanical, Electrical and Plumbing (MEP) and fire protection building systems), while taking into account the useful height required to install and move the modules with the defined dimensions onsite and/or inside the building structure.
PR7	Assembly tolerances	Precision and restrictions of assembly tolerances for component materials and integrated systems	*SLR D1.5*: It is critical to ensure the offsite and onsite restricted tolerances – the permitted degree of variance from nominal values or design specifications – when industrialising components to satisfy the overall quality goals for the assembled structure (module-module and module-onsite elements) [5]. *Interviews' results*: It is vital to guarantee that the modules are able to withstand the stresses that they are subjected to during transit, handling, and erection, thereby preventing structural/nonstructural component damage.
PR8	Legal requirements	The degree of alignment between projected modules and legal building requirements	*SLR D1.3*: When considering whether to use CI in a project, it is crucial to investigate whether there are supportive local building codes, approved local industrialised design standards of practise, technical guidelines, standards, and specifications for the design team to use when developing the modular design [6].

Table 16. Evaluation factors of the “enablers” assessing phase.

E1	**Culture and Leadership**		
Code	**Factor**	**Description**	**Source**
E1.1	Appropriate business strategies and competitiveness	The extent to which CI is in line with the company business and competitiveness strategy	*SLR D2.1*: Foreign construction firms continue to compete with local enterprises to build projects in most countries. The competitive pressures compel organizations to discover chances to meet or exceed timetables, minimize costs, and improve performance. Before adopting CI solutions, it is vital to change the company’s strategy to achieve the desired innovative competitiveness and outstanding reputation [15].
E1.2	Availability of financial and technical support and training	Availability and predisposing to access to the required financial, technical, and training support to develop a certain MiC project	*SLR D2.2*: Prior to implementing CI solutions, it is vital to ensure the owner’s ability to support the modularization concept managerially, technically, and commercially [17]. The necessary financial support must be ensured [15], and workers must be provided with training and workshops to improve their abilities to help local contractors [2, 3].
E1.3	Availability of a skilled management and supervising team	Presence of a project management and supervising team with the necessary expertise to manage the project and ensure the global containment of contracts, risk and conflicts	*SLR D2.3*: A project management and supervising team with technical skills in DfMA, supply chain and stakeholder management, project and system integration, logistical and material handling skills, production engineering, process efficiency, timing, sequencing, and scheduling is required to ensure effective coordination between the onsite and offsite work packages [9, 11, 12]. This team must understand the contract’s terms and details to coordinate all activities, processes, and teams from design to installation [8], as contractual disputes, legal and regulatory changes, and project permitting issues are all considered potential risks in offsite construction projects [5].
E1.4	Commitment and involvement throughout the project	The degree of alignment among the participants and involvement with the project execution	*SLR D2.5*: The effective implementation of MiC requires the early and extensive stakeholders commitment and the coordination of multiple trades [3, 5, 6, 7, 9, 11, 15]. A fully integrated approach and the involvement of main participants throughout the project [11, 12] allow for key decisions to be understood by all the relevant actors [8, 9].
E1.5	Culture of communication and collaboration	Ensurance of an efficient and transparent flow of information among all the project participants	*SLR D2.6*: One of the most significant MiC critical factors is the collaborative working and information exchange within project teams [8]. It allows stakeholders and partners to be included in the modularization process to maximize information sharing and reduce any errors caused by lack of knowledge or information about previous decisions and accomplishments [2, 10, 11], thereby increasing the benefits associated with the use of offsite construction methods [5, 7]. Good working collaboration and coordination enable the main stakeholders to appreciate and align with the planning, purpose, and benefits of adopting MiC [9]. It is critical to maintain a communication and collaboration culture [6] that promotes an efficient and transparent information flow system throughout the supply chain [4].
E1.6	Top management support in decision-making	Assurance of top management support in relevant decision-making points	*SLR D2.8*: It is vital to identify if there is upfront support from top management to employ CI in a project to facilitate commitment to CI at the early stage of the project lifecycle and assist supply chain decision-making [6, 9, 11].

Cont.

Table 16. Evaluation factors of the “enablers” assessing phase (Cont.).

E2	**Planning and Control**		
E2.1	**Offsite capacity**		
Code	**Factor**	**Description**	**Source**
E2.1.1	Availability of skilled workforce	Presence of skilled and experienced factory labour force	*Interviews’ results*: All levels of the offsite construction delivery chain demand a high level of technical knowledge. *SLR D3.1.1*: Regarding offsite activities, it refers to the ability to perform advanced and precise modular production operations [6], and/or the organisation’s capacity to provide the necessary training.
E2.1.2	Availability of required materials and production equipment	Ensure the availability of the necessary materials and equipment to meet the production schedule	*SLR D3.1.4*: It is critical to define the capacity and resources to produce the required industrialized components [6]. *Interviews’ results:* Subcontracting should be considered for components that the production plant is unable to develop.
E2.1.3	Ability to develop solutions to support CI	The capacity to develop and/or acquire solutions that support and align the production/construction conditions with required level of industrialization	*SLR D3.1.5*: Offsite activities require the use of tools such as moulds, jigs, and/or automated devices that are necessary for the successful completion of MiC projects but are not directly involved in production operations [6]. *Interviews’ results*: Thus, before opting to adopt CI, management should evaluate the availability and accessibility of the required auxiliary equipment as well as the development of innovative solutions to handling and moving components in the factory plant, and to promote the adequate module installation onsite.
E2.1.4	Capability to produce at the required rate	The extent to which it is possible to syncronized the required delivery and the prefabrication rates	*Interviews’ results*: Prior to adopting an industrialized solution, it is needed to determine the capacity, readiness, and expertise to assess if it is possible to produce it at the demand rate, considering the alternatives of equipment productivity and facility conditions, by dimensioning a productive system and planning manufacturing rate and schedule.
E2.1.5	Capacity to ensure the required offsite storage capacity and an inventory control system	The ability to control/align the required average stock volume and the available storage capacity	*SLR D3.1.3*: The control of the manufacturing rate and buffer space management, taking into account the dimensions of the components and modules, is one of the crucial challenges of MiC projects [4]. *Interviews’ results*: If the required capacity is not accessible under current plant conditions, the capability to rent, acquire, or develop storage alternatives must be evaluated.
E2.1.6	Capability to develop an adequate production plant layout	The possibility to ensure an appropriate production facility layout for the typology of the manufactured products	*SLR D3.1.3* *Interviews’ results*: It is vital to establish if it is possible to ensure a suitable facility layout to provide effective material flow, appropriate to the module typology (e.g., size and weight), while guaranteeing worker safety.
E2.1.7	Ability to ensure a production planning and management system	The capability of ensuring an effective offsite production planning and control strategy	*Interviews’ results*: The planning and management strategy is a critical issue when implementing an industrialized project. In fact, it has been demonstrated that improper advanced planning, scheduling, and work packaging can cause many uncertainties and disruptions along the delivery chain, including onsite assembly activities [7].
E2.1.8	Ability to guarantee a quality control system	The capability of ensuring an effective production process and final product quality control	*Interviews’ results*: Quality control was noted as a key issue while adopting mass module production. Considering the stringent quality requirements, it is critical to ensure an adequate system to enforce stability and durability specifications and required certifications, by developing prototypes and conducting quality testing and control processes [1, 6].
E2.1.9	Capacity to develop cargo securing solutions	The capability of developing cargo securing solutions to avoid non-conformities caused during modules’ transportation to site	*Interviews’ results*: Following offsite module manufacture, it is vital to ensure the most suitable transport conditions and devise solutions for preventing non-conformities during vehicle loading and unloading procedures, as well as transportation to the site location.

Cont.

Table 16. Evaluation factors of the “enablers” assessing phase (Cont.).

E2.2	**Location and site attributes**		
Code	**Factor**	**Description**	**Source**
E2.2.1	Appropriate site location	The extent to which the site’s geographical location and demographic environment are suitable for the MiC project	*Interviews’ results*: The site location is an important consideration when implementing modular solutions since it influences module supply and installation conditions. *SLR D3.2.4*: It is needed to assess if, given the site location, CI solutions are a feasible cost-effective choice [6].
E2.2.2	Required site accessibility	The extent to which site access restrictions limit the delivery of modules and components	*SLR D3.2.1*: In order to transport and install the modules, it is crucial to determine if trucks and cranes can access the building site for the proposed MiC project [6].
E2.2.3	Availability of licenses for site operations	The degree of agreement between available project site permits and building necessities	*SLR D3.2.2*: Legislative approvals and permits are necessary for construction projects, taking into account construction permits, regulations, and site operations policy [6].
E2.2.4	Suitable conditions to develop an adequate site layout	The degree of alignment between site operation space characteristics and the construction equipment and components	*Interviews’ results*: The layout of the site has a direct impact on the assembly of modules, which causes all preceding supply chain segments to halt. *SLR D3.2.3*: The site layout should not only enable an efficient flow of materials but also allow for the incorporation and operation of multiple machines [4].
E2.2.5	Availability of the required storage capacity onsite or in storing facilities close to the construction site	Adequacy of site storage area for materials and module temporary storage before assembly	*Interviews’ results*: The storing capacity between module fabrication and assembly is a primary issues of MiC projects. *SLR D3.2.3*: In addition to onsite machine operation space, it is critical to ensure temporary module storage for an efficient assembly process and to absorb the impact of demand variability [4].
E2.2.6	Module unloading, lifting, and installation restrictions	Considerations related to the site constraints that affect module unloading, lifting, and installation	*SLR D3.2.3*: Module installation is a vital step in the MiC construction process. Considering the high sensitivity to wind and rain constraints as well as the delicacy necessary to align modules and repair the joints [4], it is critical to consider restrictions connected to this phase in order to avoid module damage during unloading, lifting, and installation operations. Thus, the selection of onsite lifting equipment, particularly cranes, should be based on numerous parameters, including module weight, project height, lifting capability, and crane radius, as well as guaranteeing the proper knowledge to ensure precise and correct module installation [7].

Cont.

Table 16. Evaluation factors of the “enablers” assessing phase (Cont.).

E2.3	**Onsite activities**		
Code	**Factor**	**Description**	**Source**
E2.3.1	Availability of skilled workforce	Presence of skilled and experienced onsite labour force	*Interviews’ results*: Although fewer construction employees are involved in onsite activities, all levels of the delivery chain demand a high level of technical knowledge and skills. *SLR D3.3.1*: Regarding onsite activities, it refers to the use of powerful cranes for systematic onsite assembly of modules [6], ensuring installation to the appropriate quality standard [11].
E2.3.2	Availability of the required components and equipment	Effectively ensure the availability of the necessary materials and equipment to meet the onsite project requirements	*SLR D3.3.3, D3.3.4*: To ensure the required quality of site preparation work, it is critical to guarantee a JIT delivery strategy that maintains the site’s smooth logistics while also feeding the construction work-front with the required quantity of modules every day [1], as well as the availability of required equipment that meets the operation conditions.
E2.3.3	Ability to develop onsite solutions to support module installation	Availability of devices to aid the unloading, lifting and installation processes, and the degree of alignment between them and the onsite equipment and restrictions	*Interviews’ results*: Before opting to adopt CI, management should evaluate the availability and accessibility of the required auxiliary construction equipment as well as the development of innovative solutions to handling and moving components onsite to promote the adequate module installation.
E2.3.4	Ability to manage onsite activity	The capability of ensuring an effective onsite activity management strategy	*SLR D3.3.2*: In addition to reduced onsite construction activities, improved site activity management is a significant driver of the offsite construction paradigm since they can boost construction productivity [15]. A team capable to develop a suited site management from the contractor’s side is required to overcome the problems associated with the location and site attributes. It is critical to ensure JIT delivery and to consider controllable/uncontrollable factors that may delay module and component arrival and incorporation schedules at the site, which can be related to onsite equipment availability and will impact on-site resource utilisation, potentially resulting in additional costs [3].
E2.3.5	Ability to manage and control onsite inventory	The capability of ensuring an effective onsite inventory management strategy	*Interviews’ results*: Given the limited onsite storage space and the uniqueness and rigid design of made-to-order modules, suitable onsite inventory management is essential. *SLR D3.3.3*: Scheduling must be adjusted so that the quantity of each module manufactured precisely matches the project’s optimum quantity and time requirements [10, 11].

Cont.

Table 16. Evaluation factors of the “enablers” assessing phase (Cont.).

E2.4	**Transportation aspect**		
Code	**Factor**	**Description**	**Source**
E2.4.1	Availability of the most appropriate transport method with the required capacity	The degree to which the transport method conditions and capacity are in sync with the module attributes and the transport volume	*SLR D3.4.2*: Transportation method is one of the most identified critical challenge [3]. It is vital to guarantee local transportation methods that are in line with the required transportation capacity to supply the appropriate quantity of modules onsite when necessary [11].
E2.4.2	Availability of an adjusted road network and infrastructures	Availability of a transportation network and infrastructures adjusted to the transportation requirements	*SLR D3.4.2*: Another frequently mentioned transport issue is network capability or capacity. Due to the module weight and size, MiC may become invalid in certain locations, as the roadways, particularly city interior roads, are not meant to carry such a heavyweight [3, 6, 11]. Furthermore, enough width of the local transportation network is required, and low surrounding traffic is deemed most suited to permit smooth transportation and safe and timely delivery of modules from the supplier or production facility to the construction site [8, 9].
E2.4.3	Availability of the required transport permits	The degree of conformity between transport zone regulations and permits and module transport needs	*SLR D3.4.2*: Given the dimensions of the construction modules, it is vital to ensure that the proper permits are obtained in order to undertake the necessary heavy transportation. Furthermore, certain locations, such as urban and metropolitan areas, have transportation and traffic restrictions for large trucks, cross-border checkpoint laws, customs and excise procedures, and legal requirements [3, 4, 9].
E2.4.4	Availability of a skilled transportation management and control team	Presence of skilled transportation management and control team	*Interviews’ results*: In the planning and scheduling phase, it is vital to conduct an early logistics and transportation evaluation to identify transportation costs, critical constraints, and risks. *SLR D3.4.2*: Risk analysis and contingency planning are indeed required in order to ensure projected transportation and supply chain performance [3, 17]. It is suggested that the design and logistics teams collaborate closely with the highway team to ensure that modular sizes and weights, as well as transportation routes, are in accordance with transportation regulations, in order to avoid incurring additional costs and eliminating the time-saving benefit [4, 10].

Cont.

Table 16. Evaluation factors of the “enablers” assessing phase (Cont.).

E3	**Supply Chain Coordination**		
Code	**Factor**	**Description**	**Source**
E3.1	Availability of fabricators and suppliers	Availability of fabricators and suppliers with the required capabilities to meet project requirements	*SLR D4.1*: One of the challenges in launching MiC projects is the scarcity of fabricators [3]. The quality of these projects is determined by the quality of industrialized items, which is determined by the ability of available fabricators and suppliers to meet the project requirements [6].
E3.2	Adequate supply chain capability for CI	The ability of project participants to implement and deal with the challenges of CI and MiC projects	*SLR D4.2, D4.4*: It is critical to ensure the technical competence of the contractor and fabricator [3], as well as their expertise in orchestrating a MiC supply chain and ensuring the efficiency of logistical processes [6].
E3.3	Ability to ensure a supply chain integrated planning	The ability to plan and coordinate supply chain participants to fulfil project schedule and budget	*SLR D4.3*: The MiC supply chain implies planning the interactions among the scheduled activities through extensive risk assessments and continuous monitoring to re-plan and re-schedule the supply chain [4]. The success of MiC requires extensive coordination of linked supply chain segments prior to and during the construction process [11].
E3.4	Ability to coordinate onsite and offsite work packages	The degree of coordination between offsite production and onsite development and installation	*SLR D4.6*: Offsite and onsite operations must be efficiently coordinated in order to guarantee project continuity and avoid costly and systemic disruptions in the delivery chain [8].
E3.5	Capacity to ensure an inventory management and control system	Effectiveness of the strategy of controlling supply chain stocks to avoid module shortages onsite	*SLR D4.7*: The supply chain operations are affected by the ability to control the rate of manufacturing and buffer space management at storage facilities [4]. Inventory management and control of resources (materials and equipment) are critical to achieving the objectives of MiC projects [8].
E4	**Modelling Technology**		
Code	**Factor**	**Description**	**Source**
E4.1	Presence of relevant supportive technology (BIM)	Possibility of implementing and using building information modelling technology	*SLR D5.3*: Building information modelling is important, if not required, for any significant MiC project [6]. BIM models generate a digital representation of a project’s physical and functional characteristics and provide a platform for information sharing and knowledge exchange [9], encompassing project management from a lifecycle perspective, including planning, design of each industrialized item, and supply chain management [6].
E4.2	Capability to adapt the design for modularization and DfMA	Engineering designers’ ability to develop suitable modular solutions that foster DfMA of components and modules, using BIM	*SLR D5.2*: To develop solutions with suitability of design for modularization, manufacturing, transportation, and assembly, tolerance management, connection systems, production engineering, and value engineering, it is required skills in production engineering, module manufacturing, DfMA, and process efficiency [5, 8, 12]. *Interviews’ results*: It is necessary to examine the density of MEP system elements and building compartmentalization, as well as the fire protection solutions, to design the system lines and connections of the modules, for example.
E4.3	Capability to provide accurate design and engineering specifications	Engineering designers’ ability to develop precise detailed component design and engineering specifications documentation	*SLR D5.1*: Inaccurate engineering specifications is a leading cause of MiC project failures [12], as the functional specifications and detailed drawings dictate the work requirements of the fabricator or manufacturer [9, 11]. Thus, it is critical to ensure the required engineering designers’ expertise to develop structural designs, including detailed specifications of connections, interfaces, components, with accurate dimensional and geometric tolerances [11].

Table 17. Evaluation indicators of the “results” assessing phase.

R1	**Processes perspective**		
R1.1	**Process efficiency**		
Code	**Factor**	**Description**	**Source**
R1.1.1	Prefabrication rate	It measures the modules production rate. It must be equal or lower than the demand rate.	SCOR metric
R1.1.2	Number of orders shipped to site	Number of transports needed to deliver the modules to the site. A key metric for estimating transportation costs and environmental concerns.	SLR D6.2; SCOR metric
R1.1.3	Number of employees required	The skilled labour needs decrease in a controlled production environment as a result of easier control of the processes at various stages of development.	SLR D6.3
R1.1.4	Average labour occupancy rate	The system’s equilibrium can be expressed by the ratio of the time an employee works by the time it is available. It should not be too close to 100% and should not reflect a low use of the resource.	SLR D6.4
R1.1.5	Average stock volume	Assesses the supply and delivery efficiency.	SLR D6.4
R1.2	**Time performance**		
Code	**Factor**	**Description**	**Source**
R1.2.1	Project schedule	Contracted time for project completion.	SLR D7.1
R1.2.2	Customer order fulfilment cycle time	Expected time required to complete the project considering the project requirements, the production capacity and the defined modular units.	SCOR metric; SLR D7.2
R1.2.3	Project schedule conformance ratio[7]	The degree of conformance of expected completion time and the contracted project schedule.	SLR D7.3
R1.2.4	BIM modelling time	Time required for modelling and evaluating design and component engineering issues.	SLR D7.4
R1.2.5	Schedule construction activities cycle time	Time required for planning and schedule construction activities onsite and offsite, and the respective coordination of both.	SCOR metric; SLR D7.4
R1.2.6	Prototyping time	Expected time for required prototypes development and respective time for customer approval.	Interviews’ results
R1.2.7	Site development time	Time required for site preparation and development of the building foundations.	SLR D7.6
R1.2.8	Productive time	Expected offsite productive time (disregarding expected additional time for quality control and rework).	SLR D7.5; SCOR metric
R1.2.9	Down time for quality tests and verification	Expected time spent with quality tests and project requirements’ verification with the system down.	SLR D7.7
R1.2.10	Rework time	Estimated time spent in repairing non-conformities (it can compromise the time conformance ratio).	Interviews’ results
R1.2.11	Pick product cycle time	Expected time to pick the offsite finished products to the packing area.	SCOR metric; SLR D7.8
R1.2.12	Pack product cycle time	Time to pack the offsite final product.	SCOR metric; SLR D7.8
R1.2.13	Load vehicle cycle time	Time to load vehicles before transport the modules to the construction site (or eventual required storage facility between production plant and construction site) and generate required shipping documents.	SCOR metric; SLR D7.8
R1.2.14	Route shipments cycle time	Transportation time (if required, consider the storage time in a intermediate storage facility).	SLR D7.9; SCOR metric
R1.2.15	Time to unload modules onsite	Time necessary to unload and storage modules onsite	SCOR metric; SLR D7.8
R1.2.16	Onsite assembly time	Expected time to assembly the modular components in the building structure and complete the extra required onsite tasks to finish it.	SLR D7.10

Cont.

Table 17. Evaluation indicators of the "results" assessing phase (Cont.).

R2	**Financial perspective (Cost performance)**		
Code	**Factor**	**Description**	**Source**
R2.1	Project budget	Contracted budget for the project.	SLR D8.1
R2.2	Total operation and maintenance costs	Total costs incurred during the construction project, including costs associated with the site development phase, offsite manufacturing, and logistical activities.	SLR D8.2
R2.3	Cost conformance ratio[8]	The conformance degree of expected total project's operation cost and the contracted project budget.	SLR D8.3
R2.4	BIM modelling costs	Costs associated to the process of modelling the construction unit.	SLR D8.4
R2.5	Costs of component engineering tests	Costs associated to the assessment of design and component engineering issues.	SLR D8.4; SCOR metric
R2.6	Initial cost	Required initial investments associated to the modules' production.	SLR D8.5
R2.7	Equipment costs	Estimated costs with equipment (acquisition and maintenance costs).	SLR D8.6
R2.8	Direct labour cost	Estimated costs with workforce.	SLR D8.7; SCOR metric
R2.9	Direct material cost	Total costs of acquiring the required material for the module production. It should include an extra margin considering the probability of delivery of non-conforming units by the supplier and possible errors during production.	SLR D8.8; SCOR metric
R2.10	Cost of storage space	Costs incurred to acquire and maintain a storage warehouse.	SLR D8.11
R2.11	Onsite module unload costs	Costs incurred in the unloading and storing of modules delivered onsite.	SLR D8.11
R2.12	Materials management and planning cost	Costs incurred with the planning, scheduling and management activities.	SLR D8.11
R2.13	SCM related costs	Costs incurred with SCM.	SLR D8.11
R2.14	Transportation costs	Costs related to the transportation of modules to the construction site. It should include the costs incurred with packaging considering the transportation requirements, the most appropriated transportation method, the best transportation route and the required transportation licenses.	SLR D8.9; SCOR metric
R2.15	Onsite module installation and handling costs	Costs incurred with the installation of modules onsite, considering the necessary handling equipment.	SLR D8.10; SCOR metric
R2.16	Production indirect cost	Costs incurred with all the indirect activities related to the construction process (e.g., costs with energy, water, facility maintenance, etc.).	SLR D8.12
R2.17	Quality related costs	Estimated costs associated to the required quality tests and non-conformities repair (it can compromise the cost conformance ratio).	Interviews' results
R2.18	Construction site costs	Estimated costs of maintaining site operations during the onsite development.	Interviews' results

Cont.

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[7] Determined by customer order fulfilment cycle time/project schedule, which must be equal to or higher than 0.

[8] Determined by total operation cost/project budget, which must be equal to or higher than 0.

Table 17. Evaluation indicators of the “results” assessing phase (Cont.).

R3	**Customer perspective (Quality performance)**		
Code	**Factor**	**Description**	**Source**
R3.1	Non-conformities in finished products	Critical to identify route causes and estimate rework time, quality-related costs, and defect rate.	SLR D9.2, D9.3; SCOR metric
R3.2	Non-conformities caused by transport	Important measure to identify the ideal module features considering the transport conditions.	Interviews’ results; SLR D9.2, D9.3
R3.3	Defect rate	Estimated percentage of components that fails to meet a quality target.	Interviews’ results; SLR D9.2
R4	**People and Environment perspective**		
R4.1	**Safety performance**		
Code	**Factor**	**Description**	**Source**
R4.1.1	Frequency of occupational accidents	Key metric to measure the risk level of each performed activity and of the whole project.	SLR D10.2; SCOR metric
R4.1.2	Severity of occupational accidents	Key metric to measure the risk level of each performed activity and of the whole project.	SLR D10.2; SCOR metric
R4.1.3	Number of works at height	Measures the number of activities that expose workers to the risk of falling from heights.	SLR D10.3
R4.1.4	Weight of materials handled at height	Concerning crane capacity for handling heavy weights onsite and the risk of crushing.	Interviews’ results; SLR D10.3
R4.1.5	Number of activities that require specific Personal Protective Equipment (PPE)	The necessity of special PPE is related with the risk index of the activity under analysis.	Interviews’ results; SLR D10.4
R4.1.6	Number of activities with ergonomic risk	Activities involving critical postures to assess the ergonomic risk of manual load handling and the development of musculoskeletal issues.	Interviews’ results; SLR D10.5
R4.2	**Environmental sustainability performance**		
Code	**Factor**	**Description**	**Source**
R4.2.1	Number of environmental certifications	Important measure to evaluate the overall environmental performance of the project, based on the expected accomplished certifications.	SLR D11.2
R4.2.2	Carbon/GHG emissions	Estimates the carbon emissions involved in the construction/transportation operations.	SLR D11.1, D11.7 SCOR metric
R4.2.3	Onsite activities above the allowed sound level	Number of onsite activities performed above local sound level limit.	SLR D11.6
R4.2.4	Energy consumed (percentage of renewable energy)	Estimated required energy for performing the planned activities, highlighting the percentage derived from renewable energy sources.	SLR D11.5; SCOR metric
R4.2.5	Water consumed	Measures the water volume consumed to perform the production/construction operations.	SLR D11.3; SCOR metric
R4.2.6	Materials used	Measures the materials volume used to perform the production/construction operations.	SLR D11.4; SCOR metric
R4.2.7	Percentage of reused materials[9]	Estimates the percentage of reused materials that can be incorporated in the final product.	SLR D11.9; SCOR metric
R4.2.8	Percentage of recycled materials[10]	Estimates the percentage of recycled materials that can be incorporated in the final product.	SLR D11.9; SCOR metric
R4.2.9	Generated waste directed to disposal	Estimates the construction waste volume that goes directly to disposal.	SLR D11.10; SCOR metric
R4.2.10	Waste diverted from disposal for recycling	Estimates the construction waste volume that can be recycled into different components for another project.	SCOR metric
R4.2.11	Waste diverted from disposal for reuse	Estimates the construction waste volume that can be reused in another project.	SCOR metric

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[9] Determined by reused materials used/total materials used.

[10] Determined by recycled materials used/total material volume.

4 Case study

This chapter exposes the exploratory case study conducted to validate the suggested framework and understand how it might be further extended. The study was developed in the logistics department of the dst group, within the scope of the MiC project in collaboration with the Norman Foster Foundation.

The first subsection introduces the application context, which comprises a background description, the exploration context of modular solutions, and the ongoing MiC project (which serves as a case study) of the company where the project was developed – dst group.

The data collection process used to implement the framework is then outlined to facilitate the subsequent analysis. First, the "project requirements" are assessed, and the optimal level of granularity of the project is determined. Then, the "enablers" phase is examined to establish the feasible levels of modularization, whose corresponding supply chains are designed in order to be examined in the "results" phase.

Finally, the case study results are briefly discussed.

4.1 Contextualization

4.1.1 The dst group

The dst group was created in the 1940s by the Domingos da Silva Teixeira family (whose initials form the organisation's name) with its major activity in the construction sector. However, the group's concern for market demands and commitment to competitiveness drove it to expand its activities into synergistic business areas through the acquisition and formation of companies in a variety of markets.

The company currently employs over 2 500 people across more than 50 companies functioning in six areas: engineering and construction, environment, renewable energy, telecommunications, real estate, and ventures. Thus, in addition to developing AEC solutions, it creates sustainable products and services, provides renewable energy engineering services, operates a national fibre network, develops real estate business activities, urban rehabilitation and smart city enhancement, whilst supporting innovation projects. The management and communication between the companies are facilitated by the common location in the dst group Complex, which allows the appropriate standards of quality and excellence to be attained.

In this regard, the dst group, founded on the organizational mission of "creating sustainable business projects that contribute value to the community", brings together complementary competencies that allow it to be a national reference in the construction sector, with a turnover of 411.1 million euros in 2021. Furthermore, the group seeks to expand its international activity, with operation in eleven countries and commercial relations with fifteen countries across Europe, Africa, America, and Asia.

Based on the values of "respect", "rigour", "passion", "loyalty", "aesthetics", "courage", "ambition", "solidarity", and "responsibility", the group operates with a focus on the promotion of culture, education and training, environmental sustainability, quality, safety, and innovation and seeks to be aligned with the United Nations' sustainable development goals.

4.1.2 Modular construction in dst group

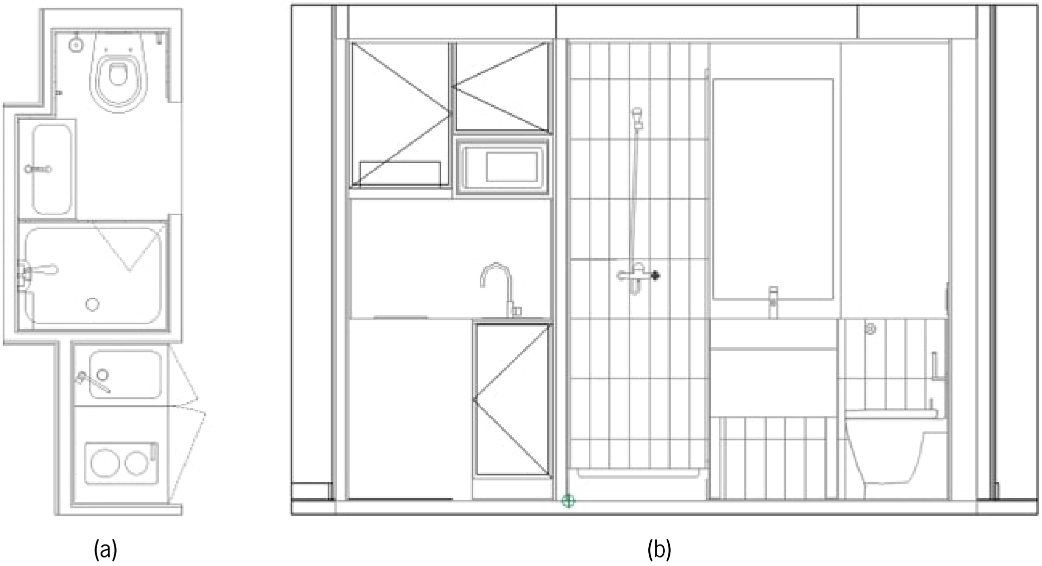
The urge to investigate CI to reach new markets led to the concept of making MiC a new component of the group's development expansion in 2019. Encouraged by top management's vision and a focus on innovation and sustainable growth, a group of experts in the company explored business opportunities, developing construction solutions, which led to the decision to embrace the cause of MiC.

The commitment to investigate industrialised solutions began with the construction industry's state-of-the-art, which is characterised by a scarcity of resources, an inability to attract new professionals, an accelerated breakdown of knowledge, low productivity, and technological backwardness. The group's innovative construction strategy turns the conventional labour-intensive construction model into a knowledge-intensive concept carried out in an industrial environment. As a result, the domains of architecture and design are advancing, ensuring the incorporation of DfMA concepts in the development of smart buildings.

Thus, the group has invested in CI in collaboration with the Norman Foster Foundation and with the contributions of some recognised architects, creating new companies in an ecosystem for the development and promotion of innovative solutions. The firm wants the new construction cluster to stand out on a national level, presenting Portugal as an international reference supplier in this building paradigm with a focus on housing, university residences, hotel business, and health. Thus, the goal of implementing modular solutions is based on the development and industrialization of disruptive construction approaches capable of reacting to market growth and new difficulties, notably in terms of environmental sustainability and protection. In this way, it is intended to create a modular and flexible construction system that can respond to the demands that architecture places on construction engineering, based on values of "determination", "resilience", "talent" and "passion".

4.1.3 The modular integrated construction project under analysis

To start establishing the disruptive CI paradigm, the dst group set out to industrialize the development of construction modules composed by a private kitchenette and a toilet for a network of university residences, initially designed to be traditionally constructed. Figure 20 illustrates the basic project configuration.


(a)

(b)

Figure 20. Technical drawings of the proposed module in (a) top and (b) side view.

Although this project began with a full MiC strategy, this CI project is used to test the developed framework. In this regard, the three-dimensional modules consisting of one toilet and a kitchenette will be the case study's unit of analysis. In this section, this modular unit is referred to as a "pod", which is a term used in the construction industry to denote pre-assembled units such as toilets produced offsite that enclose space and are transported to the site to be connected to other building elements (Goh & Loosemore, 2017).

First, the "project requirements" of the university residence are assessed in order to justify the industrialization of these specific room elements. The components and structure of the chosen module are next examined to determine the optimal level of granularity. Several levels of modularization can be considered based on this. Thus, the "enablers" framework phase is used to determine which ones are feasible in the context of the company and must be further investigated. This part is intended to establish whether or not the ideal granularity level can be developed within the company's environment and which other combinations of assembly processes can be executed offsite. In light of this, three feasible modular scenarios are offered, whose potential supply chains performance is examined in the "results" phase.

4.2 Data collection and analysis

The purpose of the case study is exploratory, with the goal of validating the proposed framework structure, suggesting how it might be implemented, and understanding how it can be further extended.

The study was implemented on these assumptions: (1) it is a primary evaluation of the viability of the framework structure; (2) it attempts to evaluate whether the factors can be easily assessed; (3) as there was no historical data, it is based on direct observation of processes and inputs from those working on the project; and (4) for confidentiality, the values are fictitious, selected as an example for demonstration purposes only. Although the results are not actual, they preserve the proportions of the real values to sustain the findings. Thus, the value gained from this case study is determined by its structure.

This section is divided into five subsections that correspond to the framework suggested phases and intermediate stages, by the proposed implementation process. In each subsection, it is described how the data was collected and analysed to achieve the desired outcomes.

4.2.1 Project Requirements evaluation

For the project requirements evaluation, the suggested factors can be evaluated, in a simple approach, by a checklist analysis. Considering the project setting and the architectural and building typology, the required factors were investigated as exposed in Table 18, considering the inputs of project managers, designers and architects involved in the MiC project under analysis.

Table 18. “Project requirements” checklist for the construction project under analysis.

Code	Factor	Checklist	Observations
PR1	Repeatability	✓	When analysing the project, architects and planners identified repeatability in rooms’ geometry and compartmentalization, having identified 598 repeated elements, with only minimum symmetric changes.
PR2	Standardization	✓	As the construction project is for a university residence, the materials, structures, and finish features are consistent across the rooms. Thus, the processes to manufacture the identified repetitive sections can be standardized.
PR3	Client’s receptivity	✓	Following a preliminary study of the project’s potential for offsite development, the possibility of industrializing the construction was communicated to the project’s client, who authorized it.
PR4	Design flexibility	✓	In accordance with the receptivity to industrialize the process, the client was willing to modify some design aspects to enable the building integration of off-site manufactured modules, adapting the design for traditional construction.
PR5	Design freezing	✓	To begin a closer investigation of the elements interfaces and module building integration, it was determined whether the design features were frozen, with no future adjustments possible. This factor was not an issue since it refers to a university residence with standardized room sections.

Cont.

Table 18. “Project requirements” checklist for the construction project under analysis (Cont.).

PR6	Building integration	✓	When employing BIM technology, it was noted that the plumbing system in the kitchenette and toilet zones was dense and complex. Offsite development would reduce the complexity of the construction activities. Also, the integration with the building MEP system and ducts and the needed functional height for installation and mobility inside the building structure had to be guaranteed.
PR7	Assembly tolerances	✓	The components’ assembly tolerances were ensured when designing the modules, while considering building integration needs, to offer a high quality product for customer approval. BIM technology was used for this factor analysis.
PR8	Legal requirements	✓	Prior to the final approval, the designers ensure that modules’ creation is in accordance with the legal requirements, considering plant conditions, transportation issues, and supportive local building regulations and specifications.

These factors, together with the project’s tight and demanding time schedule, suggested the prefabrication of volumetric modules of rooms’ toilet and kitchenette.

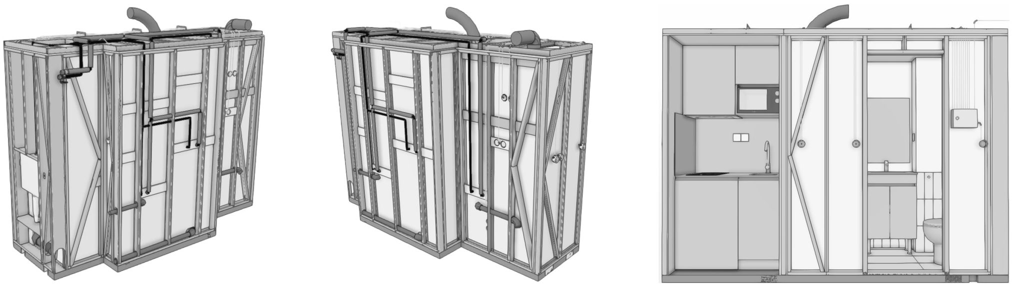
4.2.2 Optimum granularity level definition

Subsequently, the approach suggested by AlGeddawy and ElMaraghy (2013) was used to determine the optimal level of granularity. Initially, the component-based DSM is constructed by evaluating the interactions of pod components, and, then, the self-relationships are used as input to cladistics analysis.

This approach addresses the research goal of designing different levels of modularization within a construction project by defining the optimum number of sub-modules that can be assembled offsite or onsite.

Component-based DSM for the project

As shown in Figure 21, many MEP systems’ elements interact in the building structure. Also, as in any building project, the pod requires many finishing elements, which are treated as components in this analysis. Thus, the pod is made up of a significant number of components that are assembled sequentially.



(a) (b) (c)

Figure 21. Three-dimensional model of the defined pod in (a) left back view, (b) right back view, (c) front view.

Figure 22 depicts the original DSM indicating relationships among pod components (Table 19) based on an analysis of modules’ BOM and BOO, project technical drawings and three-dimensional model[1].

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[1] The order of the components in the original DSM does not adhere to any rule. To simplify the analysis, connecting components (e.g., screws) were not included.

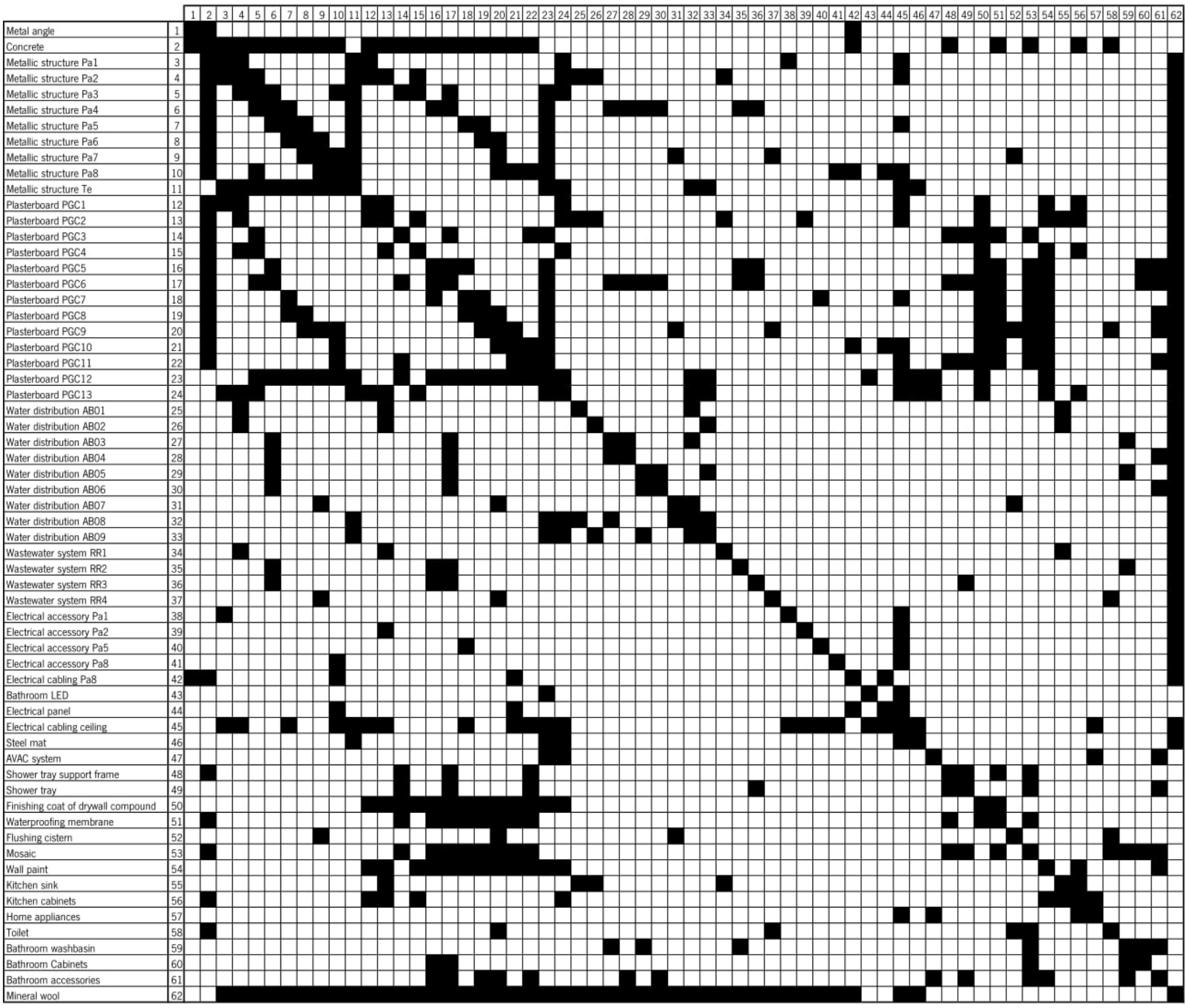

Figure 22. Pod component-based DSM.

Table 19. Pod components.

No.	Component	No.	Component	No.	Component	No.	Component
1	Metal angle	17	Plasterboard PGC6	33	Water distribution AB09	49	Shower tray
2	Concrete	18	Plasterboard PGC7	34	Wastewater system RR1	50	Finishing coat of drywall compound
3	Metallic structure Pa1	19	Plasterboard PGC8	35	Wastewater system RR2	51	Waterproofing membrane
4	Metallic structure Pa2	20	Plasterboard PGC9	36	Wastewater system RR3	52	Flushing cistern
5	Metallic structure Pa3	21	Plasterboard PGC10	37	Wastewater system RR4	53	Mosaic
6	Metallic structure Pa4	22	Plasterboard PGC11	38	Electrical accessory Pa1	54	Wall paint
7	Metallic structure Pa5	23	Plasterboard PGC12	39	Electrical accessory Pa2	55	Kitchen sink
8	Metallic structure Pa6	24	Plasterboard PGC13	40	Electrical accessory Pa5	56	Kitchen cabinets
9	Metallic structure Pa7	25	Water distribution AB01	41	Electrical accessory Pa8	57	Home appliances
10	Metallic structure Pa8	26	Water distribution AB02	42	Electrical cabling Pa8	58	Toilet
11	Metallic structure Te	27	Water distribution AB03	43	Toilet LED	59	Toilet washbasin
12	Plasterboard PGC1	28	Water distribution AB04	44	Electrical panel	60	Toilet cabinets
13	Plasterboard PGC2	29	Water distribution AB05	45	Electrical cabling ceiling	61	Toilet accessories
14	Plasterboard PGC3	30	Water distribution AB06	46	Steel mat	62	Mineral wool
15	Plasterboard PGC4	31	Water distribution AB07	47	HVAC system		
16	Plasterboard PGC5	32	Water distribution AB08	48	Shower tray support frame		

Clustering analysis

The pod component-based DSM has been used to generate the cladogram[2] displayed in Figure 23, based on the configuration of the modules' production process of the company where this project was undertaken.

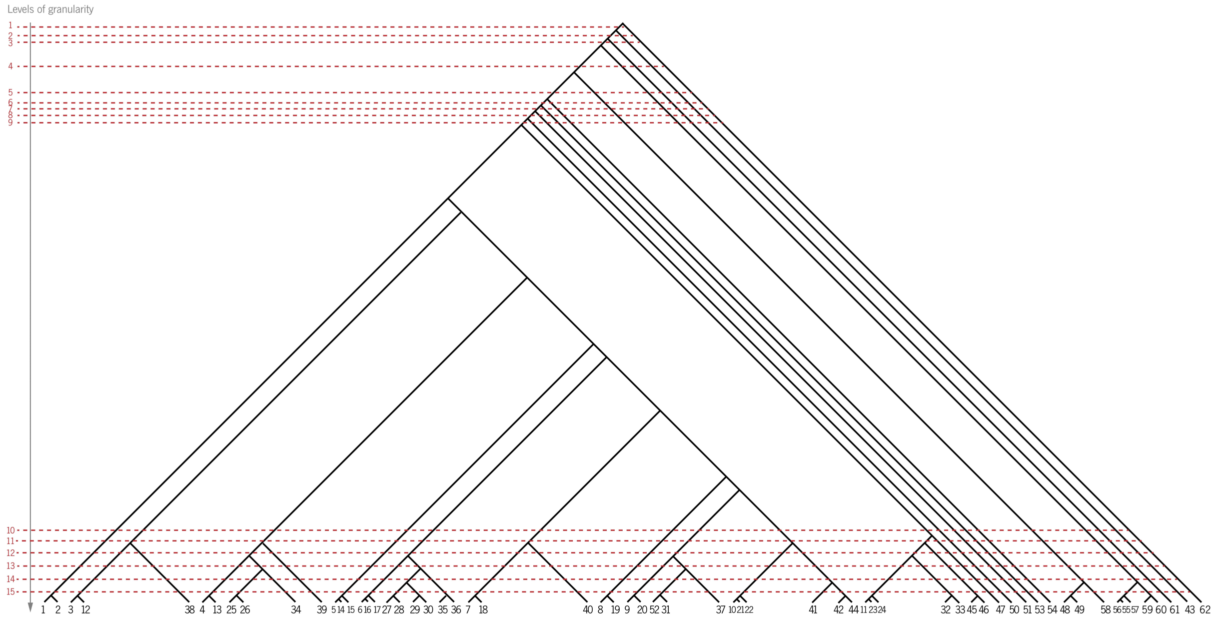

Figure 23. Resulting cladogram showing the different architecture granularity levels and components of the pod.

The cladogram typology represents the pod structure granularity map and design architecture, with 15 different levels between the top root and the terminal level of individual components. It should be noted that components related to the same technical area are portrayed as component kits in the same branch, as they require the same qualified work force and materials, even though they cannot interact in the pod structure (e.g., hydraulic and electrical systems components of each wall, as well as toilet sanitary ware and kitchenette and toilet cabinets). Furthermore, it is noted that not all cladogram nodes correspond to a granularity level. Granularity levels were defined only for nodes with practical significance in the context of construction projects. Thus, any intermediate assembly between levels 9 (which corresponds to the three-dimensional pod structure) and 10 (representing the pod walls with the required structural and MEP elements) was not regarded an individual level, since assembling certain pod walls without completing the entire three-dimensional structure has no practical relevance.

The arrangement of product components at the cladogram's terminals is used to re-shuffle components at the header row and column of the DSM. Figure 24 depicts the revised arranged DSM, highlighting the optimal granularity level sub-assemblies.

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[2] In the context of this research, the cladogram was manually generated because the exercise of identifying the components, interactions, and probable sub-assemblies served to better understand the process. However, there a few specialised software, such as Hennig86, PAUP, NONA, PeeWee, and Phylip, dedicated to cladogram creation which can cluster large data sets much faster (AlGeddawy & ElMaraghy, 2013).

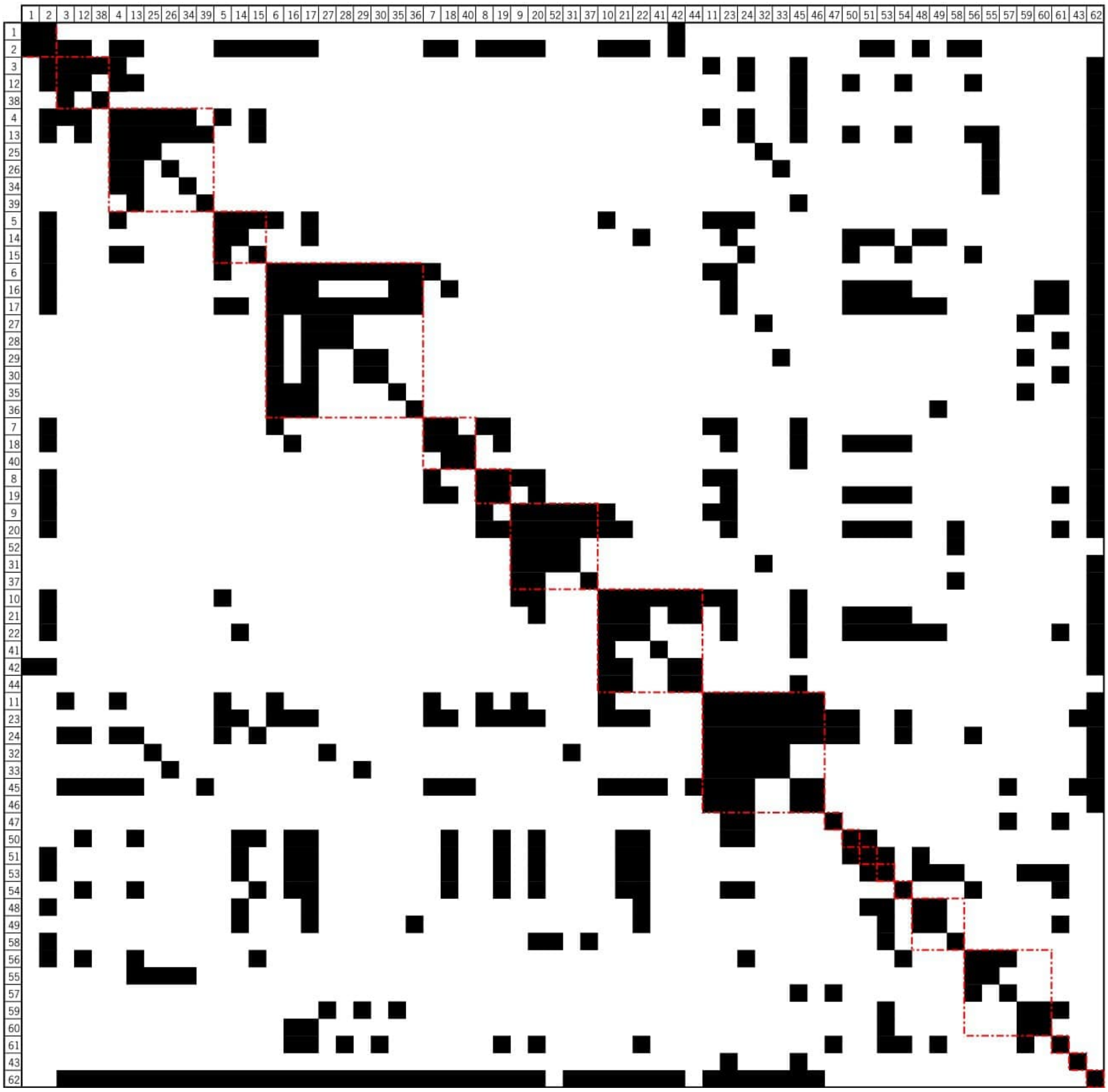

Figure 24. New clustered and sorted pod DSM highlighting the optimal granularity level sub-assemblies.

The MI is calculated for each feasible granularity level provided by cladogram topology in order to determine the optimal granularity level (i.e., the one that optimises the relationships between component clusters). The ordered DSM is used to create cluster borders at each level in order to identify “1” elements (dark cells) outside of cluster boundaries and “0” elements (blank cells) within them. Table 20 displays the calculated MI for each level, as well as the “I” and “Z” numbers of “1” and “0” elements.

Table 20. Modularity indices at each pod granularity level.

Level	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Z	3142	3026	2932	2430	2156	2080	2002	1926	1858	106	96	68	60	34	8
I	84	88	112	150	182	206	226	246	272	452	456	484	548	548	548
MI	3226	3114	3044	2580	2338	2286	2228	2172	2130	558	**552**	**552**	608	582	556

The results show that levels 11 and 12 have the lowest MI=552. Since the CI is tied to the DfMA principles, level 11 was considered the ideal granularity level to minimise inter-module component interactions. As a result, 20 component modules are identified: {1, 2}, {3, 12, 38}, {4, 13, 25, 26, 34, 39}, {5, 14, 15}, {6, 16, 17, 27, 28, 29, 30, 35, 36}, {7, 17, 40}, {8, 19}, {9, 20, 52, 31, 37}, {10, 21, 22, 41, 42, 44}, {11, 23, 24, 32, 33, 45, 46}, {47}, {50}, {51}, {53}, {54}, {48, 49, 58}, {56, 55, 57, 59, 60}, {61}, {43}, {62}. This level relates to the scenario in which two-dimensional elements are entirely assembled, excepting for the HVAC component in the pod structure ceiling, which corresponds to an one-element cluster. Moreover, finishing elements such as finish coat of drywall compound, waterproofing membrane, mosaic, and wall paint also correspond to one-element clusters, which is logical as they are isolated elements applied sequentially. This happens because finish elements are classified as pod components in this case study.

It should be noted that the ideal granularity level analysis can differ depending on the aggregation level of the bottom components in the cladogram tree. If the project was specified to test only levels within a three-dimensional system, the bottom level may correspond to level 9. Inferior levels could be analysed considering the same approach (for example, whereas components 3 to 11 were designated as “metallic structures”, they represent an assembly of metallic uprights).

Cladogram topology (Figure 23) can be deconstructed at level 11 (Figure 25) to obtain the desired pod’s architecture and granularity map. By adding nodes of sub-assemblies at each level to illustrate unions of component modules, it can be turned to a product architectural layout similar to the BOM (Figure 26).

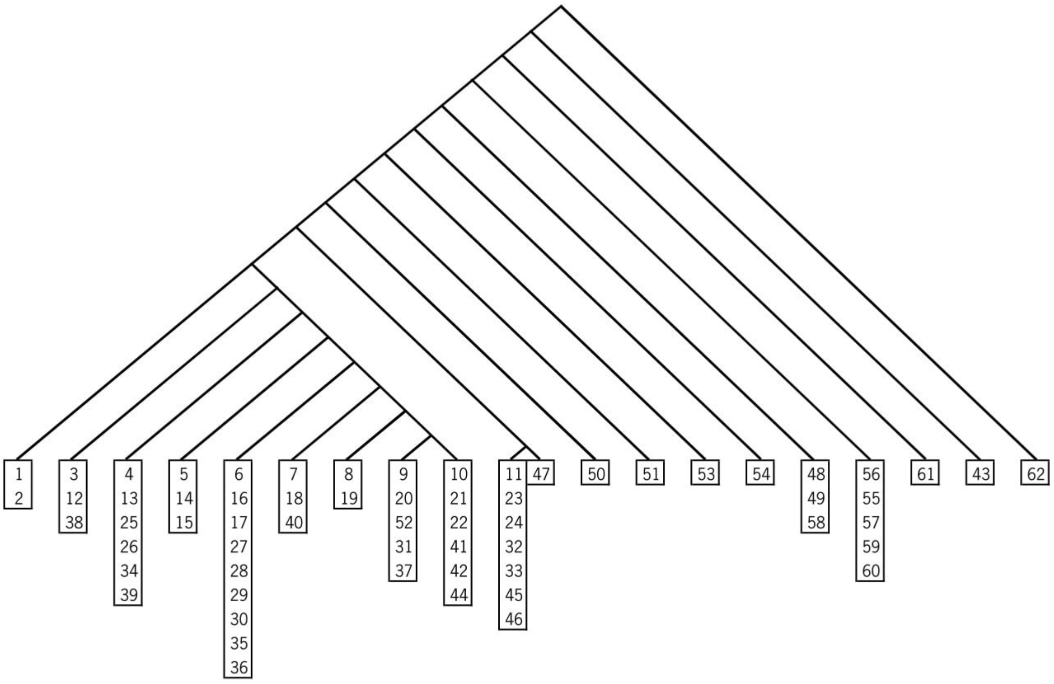

Figure 25. The dissected cladogram used to generate the architecture map of the pod.

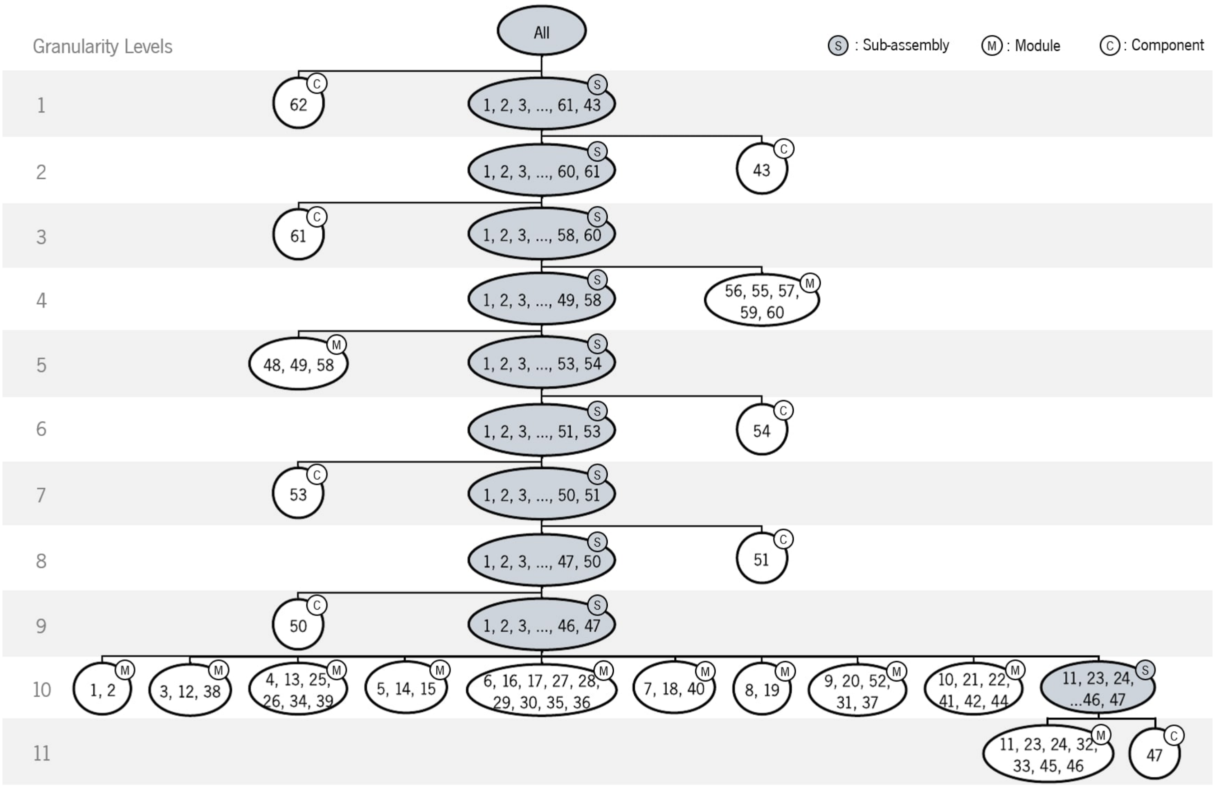

Figure 26. The pod architecture showing best granularity level and its modules and components.

From this diagram, it is clear that levels 11 and 10 relate to the pod's structural basic elements, while the remaining levels, on the other hand, refer to interior and exterior finish elements – levels 6 to 9 relate to wall finish elements; level 5 covers toilet sanitary ware (shower tray and toilet); level 4 addresses kitchenette and toilet cabinets; level 3 corresponds to applying toilet accessories; and the remaining two levels deal with installing toilet LED and external insulation, respectively.

A brief examination of MI values (Figure 27) reveals that both very coarse and very fine clustering granularity do not produce the optimal modularity measurements. AlGeddawy and ElMaraghy (2013) discovered a U-shaped relationship between the granularity level and the MI. For the analysed pod case study, modularity appears to decrease after level 12 (since the MI rose for level 13). Indeed, according to their findings for a case study on the automotive sector, modularity appears to decline at high product granularity levels. In this case study, the decline in MI after level 13 is due to the breaking up of the formed component kits whose elements are not all interacting – as can be observed, breaking up these kits simply reduces the number of "0" elements while keeping the "I" value constant. However, according to these authors, the MI is projected to decrease with lower levels of granularity. Furthermore, it should be noted that the shift from a fully assembled three-dimensional structure to its separate two-dimensional parts explains the noticeable decline between levels 9 and 10.

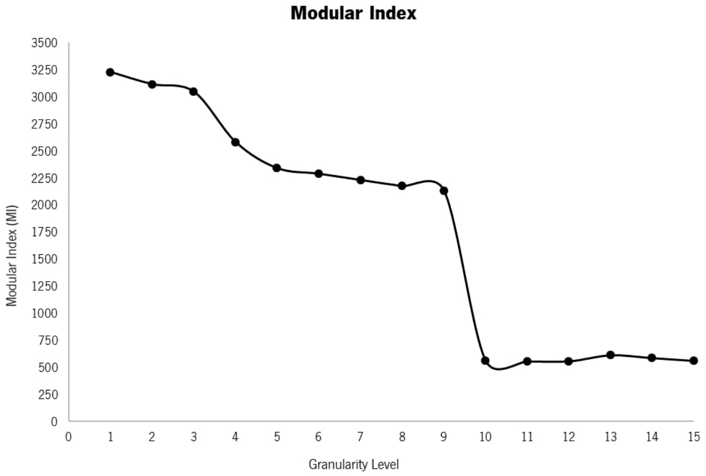

Figure 27. Relationship between product structure modularity and granularity level for the pod case study.

Two important conclusions must be drawn from this granularity analysis for the next phases: (1) how to construct multiple levels of modularization for project development, and (2) which is the best level of detailed description for the development of those modular scenarios.

As a result, it is initially proposed that the project's appropriate levels of modularization be specified using the defined granularity levels. To define distinct scenarios based on different percentages of work transferred for offsite development, it is suggested that a modularization level be built for each level of granularity based on the offsite production of the respective modules and sub-assemblies that must be further assembled onsite together with the one-element optimal clusters.

Furthermore, the granularity analysis enables the definition of the optimal level of detailed description, which, given the cluster approach, optimises the interactions between the generated elements (modules and components). As a result, the development of these fundamental elements should serve as the foundation for the building of various levels of modularization indicated for the subsequent framework phases. In other words, regardless of the level of modularization defined for the project, the optimum sub-assemblies must form the foundation of its construction, i.e., even if industrialization of structures with the incorporation of several sub-assemblies is considered, this must consist of the assembly of previously constructed optimum clusters in order to optimise the assembly process.

It should be noted that multiple analyses could be performed, resulting in cladograms with varied configurations. For instance, if it is desired to examine the performance of the development of the kitchenette and the toilet separately, two different cladograms (one with kitchenette parts and another for the toilet development) should be considered, with two separate analyses through the following framework phases. That study's results could be compared to those based on the presented cladogram.

4.2.3 Enablers evaluation

Taking the optimal clusters as the core construction elements, the identified levels of granularity correspond to distinct levels of modularization, considering the offsite production of sub-assemblies for subsequent onsite assembly[3]. Given the chosen optimal granularity level, there are 12 scenarios for project development, considering a level "0", which refers to a case in which a fully functional unit ready for installation and connection to the building's systems is completed offsite.

First, a preliminary filter of feasible scenarios is offered in light of the top management market vision by assessing the first "enablers" dimension factors with a checklist, depicted in Table 21. The "Analysis approach" summarises the analysis undertaken to determine whether each scenario meets each evaluation factor. Levels that are supported by all of the provided factors are selected for further examination.

Table 21. "Culture and leadership" factors checklist for modular scenarios associated to granularity levels 0 to 11.

Culture and leadership (E1)		**Scenarios linked to granularity levels**												**Analysis approach**
Code	**Enabler**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	
E1.1	Appropriate business strategies and competitiveness	✓									✓	✓		Analysis of the alignment between the project's industrialization level (based on the associated sub-assemblies) and company's competitiveness strategy and vision.
E1.2	Availability of financial, technical support and training	✓									✓	✓		Analysis of the investment approved to implement the project on the basis of the sub-assemblies specifications.
E1.3	Availability of a skilled management and supervising team	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Examination of the internal availability of cross-functional technical knowledge to manage, monitor, and assist the sub-modules development, assuring systems integration.
E1.4	Commitment and involvement throughout the project	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Assessment of participants' willingness to commit to and get involved in a project based on the design and development of the defined sub-assemblies.
E1.5	Culture of communication and collaboration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Analysis of the ability to establish a communication culture and channels aligned with the required agility of the information flow (between designers, fabricators, clients, etc.), considering the defined sub-assemblies.
E1.6	Top management support in decision-making	✓									✓	✓		Verification of top management permission for project execution based on sub-assemblies development and support at decision-making points throughout the project.

Only the modular scenarios linked to granularity levels 0, 9, and 10 meet all of the E1 factors. Although there is management capacity, project participants demonstrate commitment and involvement, and the communication culture is aligned with project execution under any scenario, top management does not support the ones linked to levels 2 to 8 and 11 because they are inconsistent with the project's business and competitiveness strategy, so there is no financial, technical, and decision-making support for their development (the major cause of this exclusion regards to supplier and labour management and availability). In fact, although the company intended to develop volumetric modules corresponding to level 0 to gain

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[3] It is not relevant to investigate the levels of modularization associated with lower granularity levels. However, if a company determines that it lacks the capacity (or investment potential) to develop optimal clusters, the framework can be used to analyse construction scenarios based on offsite development of lower sub-assemblies in order to assess the impact of their industrialization on construction performance.

competitive advantage and visibility in this new construction industry market, top management agreed to compare the impact of the development of those three scenarios, for case study purposes.

For further “enablers” assessment, it is also presented a checklist analysis. However, rather than examining the scenario feasibility as a whole, the remaining categories should be assessed based on each scenario’s clusters. When considering offsite production of modules and sub-assemblies for subsequent onsite assembly, E2.1 factors might not be examined for one-element clusters since they refer to the company’s “offsite capacity”, whereas the remaining categories’ factors can be investigated for all clusters.

Table 22 presents this analysis for the three scenarios approved by top management[4], considering the approach summarised in Appendix C.

Table 22. E2, E3, and E4 factors checklist for scenarios linked to granularity levels 0, 9, and 10.

Code	Level 10																			Level 9										Level 0
	M1	M2	M3	M4	M5	M6	M7	M8	M9	SA1	C2	C3	C4	C5	M11	M12	C6	C7	C8	SA2	C2	C3	C4	C5	M11	M12	C6	C7	C8	SA3
E2	**Planning and Control**																													
E2.1	**Offsite capacity**																													
E2.1.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.1.9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–	✓	✓	–	–	–	✓	–	–	–	–	✓	✓	–	–	–	✓
E2.2	**Location and site attributes**																													
E2.2.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.2.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.2.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.2.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.2.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.2.6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.3	**Onsite activities**																													
E2.3.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.3.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.3.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.3.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.3.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.4	**Transportation aspect**																													
E2.4.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.4.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.4.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E2.4.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3	**Supply Chain Coordination**																													
E3.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3.5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E4	**Modelling Technology**																													
E4.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E4.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E4.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The three scenarios may be produced considering the company’s CI capacity since, for each one, all eligible clusters for each factor satisfy the required conditions. Table 23 displays the correspondence between granularity levels and the levels of modularization which are further investigated, and a description of the industrialized components. These values were estimated by the construction experts involved in this investigation, considering “level of modularization” as the percentage of construction work done offsite.

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[4] For this analysis, to simplify clusters’ identification, it was defined the following codes: M1 – {1, 2}, M2 – {3, 12, 38}, M3 – {4, 13, 25, 26, 34, 39}, M4 – {5, 14, 15}, M5 – {6, 16, 17, 27, 28, 29, 30, 35, 36}, M6 – {7, 17, 40}, M7 – {8, 19}, M8 – {9, 20, 52, 31, 37}, M9 – {10, 21, 22, 41, 42, 44}, M10 – {11, 23, 24, 32, 33, 45, 46}, C1 – {47}, C2 – {50}, C3 – {51}, C4 – {53}, C5 – {54}, M11 – {48, 49, 58}, M12 – {56, 55, 57, 59, 60}, C6 – {61}, C7 –{43}, C8 – {62}. Additionally, SA1 – {M10, C1}, SA2 – {M1, M2, M3, M4, M5, M6, M7, M8, M9, SA1}, and SA3 stands for the assembly of all pod components.

Table 23. Pod's feasible levels of modularization.

Scenario code	Granularity level	Corresponding level of modularization	Industrialized components
I	10	25%	Walls' structure and infrastructures (MEP system components) are entirely completed offsite, ready for onsite three-dimensional assembly and finish elements application
II	9	30%	Three-dimensional structure and infrastructure (MEP system components) without finish elements completed offsite
III	0	75%	Fully functional prefabricated unit ready to be installed and connected to the building's systems (including all listed elements)

Hereafter, the scenarios under analysis are referred to as modular scenarios I, II, and III.

4.2.4 Supply chain definition

This section presents the assumptions for defining the supply chains provided for the project development alternatives, as well as a sketch of their configuration.

Since the purpose of this case study is to test the proposed framework implementation, the supply chains for the three modular scenarios were constructed assuming the same participants for simplified performance result comparison[5]. The suppliers and manufacturers were selected based on the participants of the construction project that served as the case study's foundation[6]. As a result, the three scenarios have the same locations for all suppliers and production and storage facilities. Although the modules and sub-assemblies were defined as being produced off-site and then assembled onsite with the one-element clusters, the suppliers' location and availability analysis revealed that it is more advantageous to consider direct transportation of the element clusters M11 and M12 for site location.

Figure 28 illustrates a representation of the supply chains for the development of modular scenarios I, II, and III, based on the approximate locations of the project participants. To protect the confidential information of the company's project, a list linking the suppliers to the pod components is not provided.

Given the assumption that the company has the required cross-functional technical expertise and practical orchestration and execution capability, these are the supply chains whose performance results are examined further.

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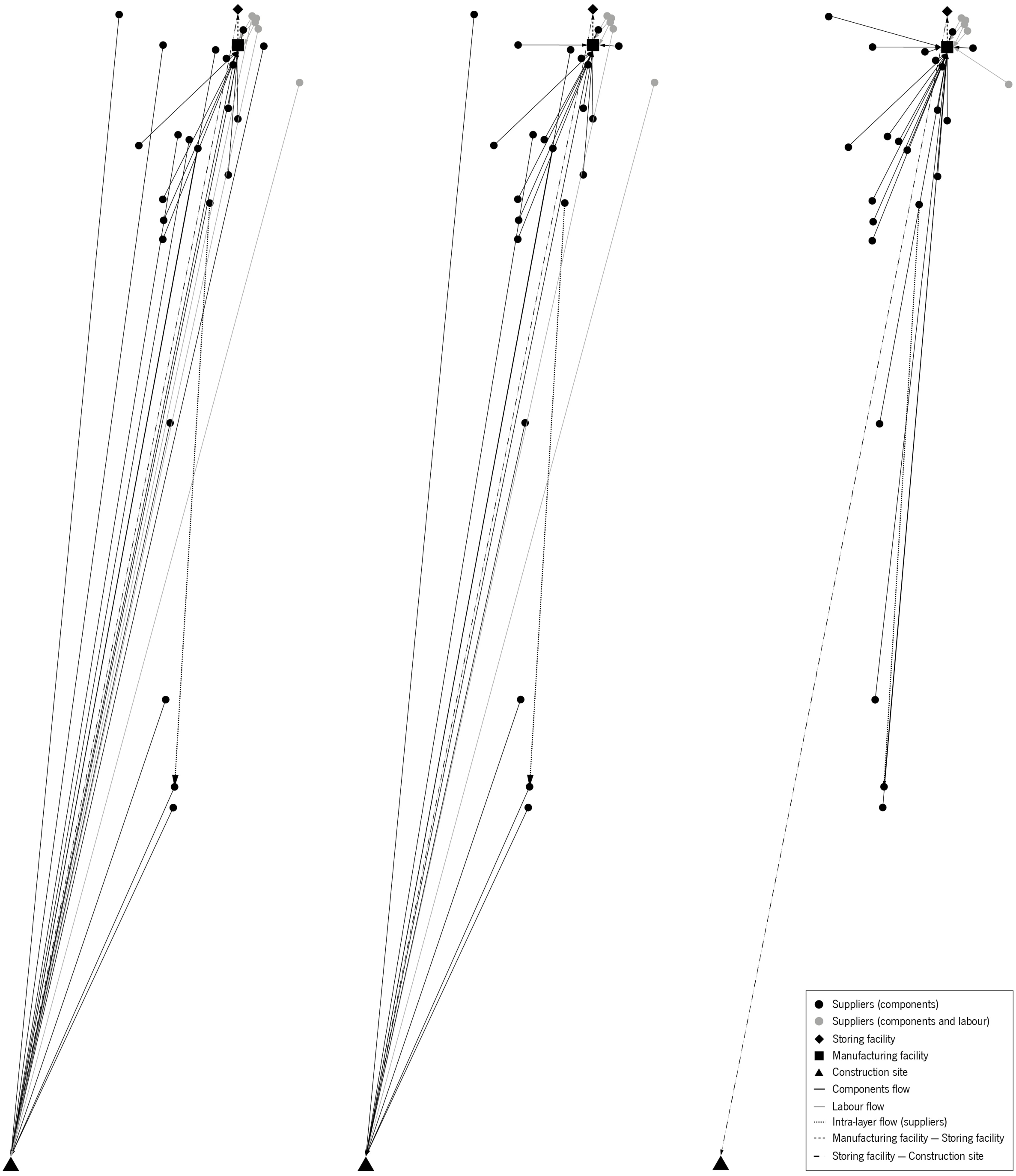
[5] For better performance results, when assigning the assembly of certain components to different sites (manufacturing facility or building site), alternative suppliers and production/storage plant locations should be considered.

[6] In the MiC project context, the construction company carried out a market research to analyse the components and solutions offered by the available suppliers and fabricators to define the project development participants.



(a) (b) (c)

Figure 28. Representation of the supply chains associated with modularization scenarios (a) I, (b) II, and (c) III.

4.2.5 Results Evaluation

This subsection provides the performance results of the three scenarios. The data reported has been generated based on the inputs of the experts involved on this investigation and on the direct observation of the ongoing project, which corresponds to modular scenario III (75% modularization). For confidentiality, the results are not actual, but they preserve the proportions of the real values to sustain the findings.

Thus, the modular scenario III performance results are fictitious data based on actual building project performance, whereas the ones for scenarios I and II are estimates based on it, considering the following assumptions: (1) the external variables (e.g.: supply chain participants, supply rates, and system capacity) remained constant across all scenarios (*ceteris paribus*); (2) the total number of employees remain constant, to simplify the subsequent comparison analysis, although it is known that onsite activities require more skilled labour[7]; (3) the same vehicle capacity for transportation operation is considered; (4) the same manufacturing and storage plants locations and characteristics are considered; and (5) the same prefabrication rate is taken, since it is based on the onsite construction demand. As the manufacturing plant has the same space and the production system gets shorter from scenario III to scenario I, assumptions (4) and (5) lead to an increase in the manufacturing plant's storage capacity and, thus, a decrease in the need for external storage space (at the rented storage plant) from scenario III to scenario I.

It must be noted that all the results estimates were validated by construction experts working on the company where the case study was implemented.

This subsection is divided into the suggested results categories R1, R2, R3, and R4 to make it easier to enhance the comprehension of the presented results. A summary of the methodology used to analyse the chosen indicators and the corresponding values for each modular scenario are provided for each one.

Processes perspective (R1)

As previously stated, the performance results for processes perspective category are divided into process efficiency (R1.1) and time performance (R1.2).

- **Process efficiency (R1.1)**

The prefabrication rate (R1.1.1) was determined considering the actual manufacturing plant operation planning and scheduling, as well as site demand. For confidentiality, the number of units produced per day is not disclosed, and the values for this variable are factored in relation to the 75% modularization target. Given this and the general assumption (3), the prefabrication rate for scenarios II and III is 1, whereas scenario I is 9. The disparity is due to the difference in modular units: 9 two-dimensional units (M2 to M11) are equivalent to one three-dimensional unit (SA2 and SA3 for scenarios II and III, respectively).

The number of orders shipped to site (R1.1.2) is calculated using the same transportation vehicle capacity and the sub-assembly sizes for each scenario. The number of vehicles needed to deliver every unit in

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[7] This presumption implies that the procedures that pass for onsite development in scenarios I and II will be more time-consuming, generate more waste, and increase project costs compared to offsite execution.

scenario III remains the same for scenario II, while for scenario I, it is predicted to decrease by half due to the size of the units and the manner in which the modules are packaged for transportation. The values provided are also factored for confidentiality.

In accordance with the general assumption (2), it was decided to keep the total number of employees needed (R1.1.3) for the planned construction activities constant throughout the modular scenarios, only changing the employees working onsite and offsite according to the activities developed onsite and offsite, respectively, in each scenario, to simplify the comparison analysis. The values offered do not relate to any actual construction scenario; they are estimates for demonstration purposes.

Based on the observed real-case cycle times, a value of the average labour occupancy rate (R1.1.4) is presented for each scenario, considering the number of employees defined and the expected productive time for onsite and offsite activities. Equation 4.1 is used for offsite operations, where $Processing\ \ time_i$ represents the productive time of manual task i. To obtain more accurate results, the labour occupancy was calculated for each essential section of the system, and the $Cycle\ \ time$ was determined by the time required to complete the most time-consuming task for each construction specialty. For onsite development, since the operations are not performed in a controlled environment, making accurate calculation of operations processing and cycle times difficult, the labour occupancy was calculated by dividing the working time by the time each employee is available for work each day.

$$Labour\ occupancy\ rate_{offsite} = \frac{\sum_{i \in \{manual\ \ operations\}} Processing\ \ time_i}{Cycle\ \ time\ \times No.\ employees} \tag{4.1}$$

Finally, the average stock volume (R1.1.5) of each scenario is based on the resource needs of the observed process. Note that, since there was no record of the material spent on site to complete the installation of the modules in the real scenario (since this material is assured by the building constructor), the onsite stock relating to the installation was disregarded (indicated by "–" for scenario III), when comparing the scenarios under study. As this value would be the approximately the same for all scenarios, this assumption does not affect the comparison results. Furthermore, rather than just presenting the average stock value, it was thought vital to indicate the percentage of used space considering offsite storage space availability (to determine this percentage, all forms of stock in both manufacturing and storage facilities are included).

Given this, Table 24 displays the process efficiency results for modular scenarios I, II, and III.

Table 24. Process efficiency results for modular scenarios I, II, and III.

R1.1	**Process efficiency**		**Modular scenarios**	
Code	**Metric**	**I**	**II**	**III**
R1.1.1	Prefabrication rate	9	1	1
R1.1.2	Number of orders shipped to site	0,5	1	1
R1.1.3	Number of employees required	62 employees	62 employees	62 employees
	Offsite	23 employees	28 employees	43 employees
	Onsite	39 employees	34 employees	19 employees
R1.1.4	Average labour occupancy rate	$\simeq$ 77,88 %	$\simeq$ 64,89 %	$\simeq$ 64,97 %
	Offsite	$\simeq$ 85,59 %	$\simeq$ 54,64 %	$\simeq$ 61,28 %
	Onsite	$\simeq$ 73,33 %	$\simeq$ 73,33 %	$\simeq$ 73,33 %
R1.1.5	Average stock volume	2 456,0 m^3	5 543,2 m^3	5 362,0 m^3
	Offsite	2 289,1 m^3 ($\simeq$ 90,9 %)	5447,5 m^3 ($\simeq$ 94,0 %)	5 362,0 m^3 ($\simeq$ 89,2 %)
	Onsite	166,9 m^3	95,7 m^3	–

- **Time performance (R1.2)**

The major purpose of time performance results analysis is to establish if the development of each scenario (considering the coordination of offsite and onsite activity) can be completed within the contractual project completion deadline. Thus, although all of the selected time performance metrics must be monitored, the project schedule conformance ratio (R1.2.3) is the most essential one to be studied and compared amongst the scenarios under consideration, as it represents a percentage of project schedule fulfilment.To preserve confidentiality, the values are fictitious and offered in time units (t.u.) to prevent disclosing the order of magnitude of time metrics.

Microsoft Project was used to simplify activity scheduling across the project extension[8]. Appendix D contains the outputs of this analysis and the assumptions made to schedule the presented activities. Although it is recommended to read it for further comprehension of the values offered, some general considerations are stated here to easily understand the results on Table 25:

- To simplify the time performance results comparison, additionally to the duration of each activity expressed by the selected indicators, the respective scheduled Starting date (SD) and Finishing date (FD) are displayed, in t.u., based on Microsoft Project results. This values take just working days from the first activity starting date as “t.u. 1”, the lags between the starting time of different activities, and their recurrence and expected duration. The aim is to make it easier to determine the project completion date (R1.2.1), which corresponds to the maximum activity FD, and, therefore, to identify the project schedule compliance ratio for each modular scenario;

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[8] It should be noted that this Microsoft tool was not used to its full capacity, with all of the functions that add complexity to the project planning and management, instead being used simply to promptly determine the conclusion dates of the specified activities based on their expected duration and recurrence.

- The complexity of the produced unit is assumed to have no effect on BIM modelling time (R1.2.4) and prototyping time (R1.2.6), because it is always necessary to model the complete volumetric unit (toilet + kitchenette) to analyse component interfaces;
- Site development time (R1.2.7) is independent of the modular scenario, as the onsite preparation work is not affected by the planned changes. It is provided to aid in the scheduling, as all operations must be arranged with the goal of fulfilling the construction needs in accordance with the JIT philosophy (i.e., onsite supplying the appropriate amount of modules when the building structure is ready to receive them);
- Productive time (R1.2.8), downtime for quality tests (R1.2.9), and rework time (R1.2.10) are shown as a sum since it is only possible to estimate the required production time, adding extra time for necessary repairs and tests, whose occurring moments are obviously unknown;
- To simplify the determination of pick product cycle time (R1.2.10), it is divided into the time required to complete the three tasks related with product picking: (1) module cleaning time[9], (2) time to apply mineral wool, and (3) time to attach wheels and move the module;
- Related to load vehicle cycle time (R1.2.13), a fictitious number of vehicles is provided, based on a given transportation capacity, to establish how many times this activity is performed;
- The time to unload modules onsite (R1.2.15) and onsite assembly (R1.2.16) values are provided in time to accomplish the tasks for all the modules transported;
- The values offered for onsite assembly (R1.2.16) include the time required to undertake the activities required to properly finish installation of the modules transported in each vehicle, completing all project requirements.

Given this, and considering that the project schedule is defined as 408 t.u., and the customer order fulfilment cycle time is given by the maximum FD of the scheduled activities, the project schedule conformance ratios are determined.

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[9] The value for scenario I involves cleaning the module and placing it on the easel for shipping.

Table 25. Time performance results for modular scenarios I, II, and III.

R1.2	**Time Performance**	**Modular scenarios**								
Code	**Metric**	**I**			**II**			**III**		
R1.2.1	Project schedule	408 t.u.								
R1.2.2	Customer order fulfilment cycle time	**450 t.u.**			**449 t.u.**			**354 t.u.**		
R1.2.3	Project schedule conformance ratio	**110,29 %**			**110,05 %**			**86,76 %**		
		Value	**SD**	**FD**	**Value**	**SD**	**FD**	**Value**	**SD**	**FD**
R1.2.4	BIM modelling time	24 t.u.	1	24	24 t.u.	1	24	24 t.u.	1	24
R1.2.5	Schedule construction activities cycle time	78 t.u.	1	78	84 t.u.	1	84	90 t.u.	1	90
	Manufacturing plant projection	64 t.u.	–	–	66 t.u.	–	–	69 t.u.	–	–
	Scheduling systems and flows	14 t.u.	–	–	18 t.u.	–	–	21 t.u.	–	–
R1.2.6	Prototyping time	48 t.u.	66	113	48 t.u.	66	113	48 t.u.	66	113
R1.2.7	Site development time	102 t.u.	135	236	102 t.u.	136	237	102 t.u.	146	247
R1.2.8	Productive time	115 t.u.	–	–	116 t.u.	–	–	119 t.u.	–	–
R1.2.9	Downtime for quality tests	0 t.u.	–	–	0 t.u.	–	–	0 t.u.	–	–
R1.2.10	Rework time	6 t.u.	–	–	6 t.u.	–	–	13 t.u.	–	–
	Time to repair non-conformities	5,43 t.u.	–	–	5,43 t.u.	–	–	12,46 t.u.	–	–
	Re-inspection time	0,35 t.u.	–	–	0,35 t.u.	–	–	0,55 t.u.	–	–
	(R1.2.8 + R1.2.9 + R1.2.10)	121 t.u.	116	236	122 t.u.	116	237	132 t.u.	116	247
R1.2.11	Pick product cycle time	0,0031 t.u./module	138	237	0,1458 t.u./module	139	238	0,2292 t.u./module	149	248
	Module cleaning time	0,0031 t.u./module	–	–	0,0833 t.u./module	–	–	0,0833 t.u./module	–	–
	Time to apply mineral wool	–	–	–	–	–	–	0,0833 t.u./module	–	–
	Time to attach wheels and move the module	–	–	–	0,0625 t.u./module	–	–	0,0625 t.u./module	–	–
R1.2.12	Pack product cycle time	0,0104 t.u./module	138	237	0,0625 t.u./module	137	238	0,0625 t.u./module	149	248
R1.2.13	Load vehicle cycle time	0,2292 t.u./vehicle	242	440	0,25 t.u./vehicle	176	441	0,25 t.u./vehicle	168	352
	Vehicles manufacturing plant – construction site	50 vehicles	–	–	36 vehicles	–	–	18 vehicles	–	–
	Vehicles manufacturing plant – storage facility	0 vehicles	–	–	64 vehicles	–	–	82 vehicles	–	–
	Vehicles storage facility – construction site	0 vehicles	–	–	64 vehicles	–	–	82 vehicles	–	–
R1.2.14	Route shipments cycle time	–	243	441	–	176	442	–	168	353
	Transports to construction site	0,625 t.u./transport	–	–	0,625 t.u./transport	–	–	0,625 t.u./transport	–	–
	Transports manufacturing plant – storage facility	0,0417 t.u./transport	–	–	0,0417 t.u./transport	–	–	0,0417 t.u./transport	–	–
R1.2.15	Time to unload modules onsite	0,125 t.u./vehicle	243	441	0,25 t.u./vehicle	244	442	0,25 t.u./vehicle	254	353
R1.2.16	Onsite assembly time	7,5 t.u./vehicle	245	**450**	6,2 t.u./vehicle	245	**449**	1 t.u./vehicle	255	**354**

Financial perspective (R2)

The selected indicators are used to tally the overall operation and maintenance costs (R2.2), considering the supply chain processes between suppliers and the construction site, to compare the economic sustainability of each modular scenario. The major goal, as with the preceding results category, is to establish whether each scenario can be developed within the contractual project budget, which may be assessed by dividing R2.2 by the project budget (R2.1), expressed by the cost conformance ratio (R2.3).

Again, the costs offered in Table 26 are fictitious, but each parcel reflects a true percentage of the total costs, ensuring a more accurate analysis. To better understand it, some considerations are taken:

- BIM modelling costs (R2.4) remain constant across modular scenarios because it is always necessary to model the complete volumetric unit to analyse component interfaces;
- Although the prototyping time is scheduled to be the same for all scenarios, the costs of component engineering tests (R2.5) differ because, as the modularization percentage decreases, fewer resources are assigned to the prototyping process (materials and labour);
- As the same manufacturing plant is used, the initial cost (R2.6) for acquiring and preparing it for the production of each scenario's components remains constant;
- Regarding direct labour costs (R2.8), although the total number of employees is the same, from scenario III to scenario I, the offsite costs decrease with the reduction of the number of employees assigned to offsite activity, and, as found in the literature, not only is onsite labour more expensive, but it also takes more time to complete the scheduled tasks (considering that the number of employees is constant for all activities, regardless of whether they are carried out offsite or onsite);
- As the cost of storage space (R2.10) refers to the costs of renting additional metres squared in an external storage plant, it drops as the modularization level and the need for extra space decrease;
- Since the same teams and management resources are considered, the costs associated with materials management and planning (R2.11) and SCM (R2.12) are the same for all scenarios;
- The costs for onsite module unloading (R2.11) and installation and handling (R2.15) only include the costs for auxiliary materials used to support these operations; labour costs are included in direct labour costs (R2.8), in this case related to the "onsite" parcel;
- Moreover, also related to R2.15, the costs of materials used in installation that are directly related to

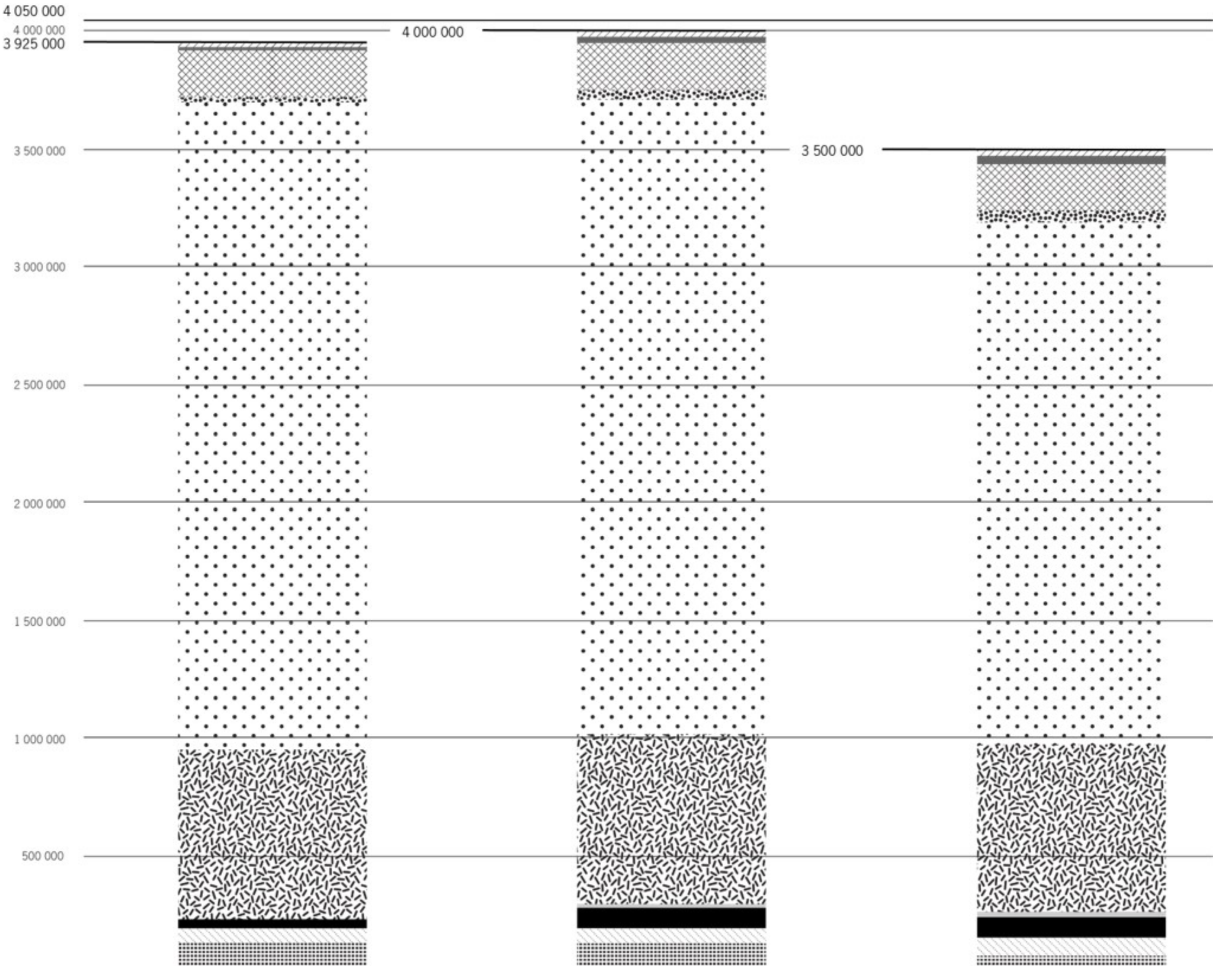
module building (rather than auxiliary components) are included in the direct material costs (R2.9);

- The “components’ reception” parcel of the transport costs (R2.14) only refers to the reception of the concrete bases (subcontracted production), as the remaining materials reception costs are subsumed into R2.9; this value is null for the first scenario, as it is not necessary to subcontract the production of concrete bases (the concrete is applied directly during onsite assembly);
- Finally, as construction site costs (R2.18) refer to onsite operations maintenance costs, it reduces from scenario I to scenario III, as the onsite required time decreases.

Table 26. Cost performance results for modular scenarios I, II, and III.

R2	**Cost Performance**	**Modular scenarios**		
Code	**Metric**	**I**	**II**	**III**
R2.1	Project budget	4 050 000,00 €		
R2.2	Total operation and maintenance costs	**3 925 500,00 €**	**4 000 000,00 €**	**3 500 000,00 €**
R2.3	Cost conformance ratio	**96,9 %**	**98,8 %**	**86,4 %**
R2.4	BIM modelling costs	9 000,00 €	9 000,00 €	9 000,00 €
R2.5	Costs of component engineering tests	14 000,00 €	26 000,00 €	35 000,00 €
	Material costs	2 000,00 €	4 000,00 €	10 000,00 €
	Labour costs	12 000,00 €	22 000,00 €	25 000,00 €
R2.6	Initial cost	200 000,00 €	200 000,00 €	200 000,00 €
	Material for manufacturing plant	9 000,00 €	9 000,00 €	9 000,00 €
	Equipment for manufacturing plant	180 000,00 €	180 000,00 €	180 000,00 €
	Manufacturing plant infrastructure	11 000,00 €	11 000,00 €	11 000,00 €
R2.7	Equipment costs	22 000,00 €	40 000,00 €	50 000,00 €
R2.8	Direct labour costs	2 725 000,00 €	2 695 000,00 €	2 220 000,00 €
	Offsite	725 000,00 €	945 000,00 €	2 000 000,00 €
	Onsite	2 000 000,00 €	1 750 000,00 €	220 000,00 €
R2.9	Direct material costs	720 400,00 €	720 000,00 €	710 000,00 €
R2.10	Costs of storage space	– €	16 000,00 €	23 000,00 €
R2.11	Onsite module unload costs	600,00 €	5 000,00 €	5 000,00 €
R2.12	Materials management and planning cost	2 000,00 €	2 000,00 €	2 000,00 €
R2.13	SCM related costs	2 000,00 €	2 000,00 €	2 000,00 €
R2.14	Transport costs	38 000,00 €	86 500,00 €	86 500,00 €
	Components’ reception	– €	10 500,00 €	10 500,00 €
	Expedition to storage facility	8 000,00 €	16 000,00 €	16 000,00 €
	Expedition to construction site	30 000,00 €	60 000,00 €	60 000,00 €
R2.15	Onsite installation and handling costs	– €	6 000,00 €	6 000,00 €
R2.16	Production indirect costs	64 450,00 €	65 000,00 €	78 000,00 €
	PPE	3 000,00 €	3 000,00 €	3 000,00 €
	Structure maintenance costs	5 450,00 €	5 500,00 €	6 500,00 €
	Fixed costs	54 500,00 €	55 000,00 €	67 000,00 €
	Office material costs	1 500,00 €	1 500,00 €	1 500,00 €
R2.17	Quality related costs	2 550,00 €	2 500,00 €	2 000,00 €
R2.18	Construction site costs (common site work)	125 500,00 €	125 000,00 €	71 500,00 €

For an easier comparison between the financial results, Figure 29 presents them in a visual format.



		Modular scenario I (25% modularization)
▨	Other costs (R2.4, R2.11, R2.12, R2.13, R2,17)	16 150 €
■	Costs of component engineering (R.5)	14 000 €
▩	Initial cost (R2.6)	200 000 €
⁙	Equipment costs (R2.7)	22 000 €
∴	Direct labour costs (R2.8)	2 750 000 €
▧	Direct material costs (R2.9)	720 400 €
■	Transport cost (R2.14)	38 000 €
▤	Production indirect cost (R2.16)	64 450 €
▦	Construction site costs (R2.18)	125 500 €

		Modular scenario II (30% modularization)
▨	Other costs (R2.4, R2.11, R2.12, R2.13,R2.15, R2,17)	26 500 €
■	Costs of component engineering (R.5)	26 000 €
▩	Initial cost (R2.6)	200 000 €
⁙	Equipment costs (R2.7)	40 000 €
∴	Direct labour costs (R2.8)	2 695 000 €
▧	Direct material costs (R2.9)	720 000 €
□	Costs of storage space (R2.10)	16 000 €
■	Transport cost (R2.14)	86 500 €
▤	Production indirect cost (R2.16)	65 000 €
▦	Construction site costs (R2.18)	125 000 €

		Modular scenario III (75% modularization)
▨	Other costs (R2.4, R2.11, R2.12, R2.13,R2.15, R2,17)	26 500 €
■	Costs of component engineering (R.5)	35 000 €
▩	Initial cost (R2.6)	200 000 €
⁙	Equipment costs (R2.7)	50 000 €
∴	Direct labour costs (R2.8)	2 220 000 €
▧	Direct material costs (R2.9)	710 000 €
□	Costs of storage space (R2.10)	23 000 €
■	Transport cost (R2.14)	86 500 €
▤	Production indirect cost (R2.16)	78 000 €
▦	Construction site costs (R2.18)	71 500 €

Figure 29. Bar chart for cost performance comparison between modular scenarios I, II, and III.

Customer perspective (R3)

It is essential to assess how each scenario performs in terms of product quality from the customer perspective. It should be noted that the nature of the modules accounts for the high values for estimated non-conformities. In fact, the numerous construction-related tasks included have a chance for error. For instance, due to the project dimensions, many non-conformities in painting and bitumen application — which are often the operations with the highest non-conformity occurrences — can be recorded in the same module. These anomalies, on the other hand, can be quickly and easily corrected, involving approximately 0,16 percent of the total project expenditures for the 75% modularization scenario, for example.

Given this, it was decided to display the defect rate (R3.3) values in units per module rather than percentages to facilitate comprehension — the average expected number of non-conformities identified per finished unit, considering all components and procedures involved. As expected, as the number of operations developed in a controlled production environment decreases, this value increases. Furthermore, as previously stated, the number of non-conformities in the offsite developed units of scenarios I and II does not differ significantly, as the majority of the defects in the production of the volumetric units of the second scenario are detected in the two-dimensional elements (products of the first scenario). It should be noted that, while the module unit differs from scenario I to scenarios II and III, the value for finished products is constant since it is assumed as the fully unit “toilet and kitchenette”.

Table 27 displays the quality performance fictitious estimates for the analysed modular scenarios, reported by the quality team managing the MiC project that served as the basis for this case study.

Table 27. Quality performance results for modular scenarios I, II, and III.

R3	**Quality Performance**	**Modular scenarios**		
Code	**Metric**	**I**	**II**	**III**
R3.1	Non-conformities in finished products	2 740 occurrences	2 735 occurrences	2 140 occurrences
	Offsite	150 occurrences	155 occurrences	2 140 occurrences
	Onsite	2 590 occurrences	2 580 occurrences	0 occurrences
R3.2	Non-conformities caused by transport	0 occurrences	0 occurrences	2 occurrences
R3.3	Defect rate (occurrences/module)	4,6	4,6	3,6
	Non-conformities detected	2 740 occurrences	2 735 occurrences	2 142 occurrences
	Number of finished products	598 units	598 units	598 units

People and Environment perspective (R4)

As the first performance results category, people and environment perspective is divided into two subcategories: safety performance (R4.1) and environmental sustainability performance (R4.2).

- **Safety performance (R4.1)**

To measure the safety performance results, the approach offered by the International Labour Organization (ILO) is used as a foundation for studying the frequency (R4.1.1) and severity (R4.1.2) of the predicted occupational accidents as it is implemented in the company where this case study was carried. As a result, Equations 4.2 and 4.3 are used and the results are examined based on Table 28.

$$Frequency\ \ index = \frac{No.\ accidents \times 1 \times 10^6}{Man - hours\ worked} \tag{4.2}$$

$$Severity\ \ index = \frac{No.\ lost\ \ days \times 1 \times 10^6}{Man - hours\ worked} \tag{4.3}$$

Table 28. ILO proposed levels for analysing frequency and severity levels.

Frequency index	Level	Severity index
< 10	**1**	< 250
10 – 25	**2**	250 – 500
25 – 50	**3**	500 – 1000
50 – 75	**4**	1000 – 2000
> 75	**5**	> 2000

For instance, when using the ILO table to analyse the results for modular scenario III, the frequency index is in the centre of the table (level 3) and the severity index is at level 2. Thus, while the frequency rate for this scenario is substantial, the accidents that happen are not serious. It can be explained by the fact that this is a newly introduced process in which assembly techniques must still be optimized to avoid risks.

Due to confidentiality, the auxiliary metrics used to calculate R4.1.1 and R4.1.2 are not disclosed. The values presented are based on the safety team's estimates of the number of accidents and the corresponding number of days lost offsite and onsite, taking into account the values offered for workers assigned to offsite and onsite work, as well as the respective working hours required for performing the defined operations.

Moreover, the total number of operations presented in R4.1.3, R4.1.5, and R4.1.6 is provided to improve understanding of the representativeness of those metrics. Note that the value was determined at a macro level (e.g., plasterboard and metallic structure assembly) – which cannot be disclosed due to confidentiality – and it is constant, since the production is based on the optimal clusters defined on DfA principles.

Taking these considerations, Table 29 shows the estimated safety results for the scenarios under study, offered by the safety team managing the project that served as the basis for this case study..

Table 29. Safety performance results for modular scenarios I, II, and III.

R4.1	**Safety Performance**	**Modular scenarios**					
Code	**Metric**	**I**		**II**		**III**	
R4.1.1	Frequency of occupational accidents	54,64	(level = 4)	57,37	(level = 4)	32,73	(level = 3)
R4.1.2	Severity of occupational accidents	366,63	(level = 2)	384,89	(level = 2)	229,12	(level = 2)
R4.1.3	Number of works at height	9	/52	9	/52	2	/52
R4.1.4	Weight of materials handled at height[10]	56,6	kg	226,6	kg	316,6	kg
R4.1.5	Number of activities that require specific PPE[11]	37	/52	36	/52	18	/52
R4.1.6	Number of activities with ergonomic risk	4	/52	3	/52	2	/52

It must be noted that, although no metric related to building safety was selected, it became clear during the data collection process that it is possible to rule out a construction scenario for reasons of building safety (e.g., the tightness of the fire protection system might impede the industrialization of certain components)

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[10] The elevated elements evaluated are cabinets, ceiling structure, HVAC components, and the modules of each scenario.

[11] Helmets were designated as specific PPE since they are not required for offsite operations.

- **Environmental sustainability performance (R4.2)**

In terms of environmental sustainability performance data, the following presumptions must be considered:

- As ISO 14001 is implemented in the organization, all scenarios are regarded as having one environmental certification (R4.2.1). However, as there are no renewable energy sources, it is assumed that there is no renewable energy in all cases;
- It was decided not to present values for carbon emissions (R4.2.2) because there is no specified method to estimate them at the company. However, it could be determined based on the electricity used in manufacturing processes and the carbon associated with the required transports;
- The materials used values (R2.6) are estimated based on the module final weight and the expected rework spending materials and construction waste generated for each scenario;
- Because this is the first CI project and there is no left-over stock from previous projects, 0 percent of reused (R4.2.7) and recycled components (R4.2.8) are assumed to be incorporated in the generated modules for all case scenarios. Moreover, architects do not want to incorporate recycled materials into the construction project due to material resistance concerns;
- Finally, the percentages in R4.2.9, R4.2.10, and R4.2.11 show the overall waste for each scenario.

Given this, Table 30 shows the environmental sustainability results for the analysed modular scenarios. Again, the values are fictitious estimations and offered exclusively for demonstrative purposes.

Table 30. Environmental sustainability performance results for modular scenarios I, II, and III.

R4.2	**Environmental sustainability performance**	**Modular scenarios**		
Code	**Metric**	**I**	**II**	**III**
R4.2.1	Number of environmental certifications	1	1	1
R4.2.2	Carbon/GHG emissions	–	–	–
R4.2.3	Onsite activities above the allowed sound level	2	1	0
R4.2.4	Energy consumed (percentage of renewable energy)	1 449,40 kWh (0%)	1430,24 kWh (0%)	1277 kWh (0%)
R4.2.5	Water consumed	200 L	200 L	200 L
R4.2.6	Materials used	939 077,2 kg	939 077,2 kg	898 528 kg
R4.2.7	Percentage of reused materials	0 %	0 %	0 %
R4.2.8	Percentage of recycled materials	0 %	0 %	0 %
R4.2.9	Generated waste directed to disposal	38 721,2 kg (94,8 %)	38 696,2 kg (94,8 %)	500 kg (19,88 %
R4.2.10	Waste diverted from disposal for recycling	1 680 kg (4,1 %)	1 680 kg (4,1 %)	1 450 kg (57,65 %)
R4.2.11	Waste diverted from disposal for reuse	448 kg (1,1 %)	448 kg (1,1 %)	565 kg (22,47 %)

4.3 Case study findings

In this chapter, the construction project was dissected based on the proposed framework implementation phases. After assessing the project's requirements, it was determined that it had modular potential. The adequate granularity level was defined by decomposing the structure into its basic components and analysing their critical interfaces using a component-based DSM approach. Based on the first enablers category, three modular scenarios (25%, 30%, and 75% of modularization) were chosen and respective supply chains were sketched. As all of the sub-assemblies involved in the development of the scenarios met the remaining "enablers" factors, ensuring company's development capacity, performance results were estimated based on direct observation of production operations and construction experts' opinions.

As previously stated, in terms of **process efficiency (R1.1)**, there is no difference in the prefabrication rates or the number of employees in charge of project development. Furthermore, no significant differences exist between scenarios in terms of the average labour occupancy rate.

Due to the smaller size of the prefabricated units, scenario I stands out in the number of orders shipped to site, requiring half of the vehicles, and with regard to average stock volume. It should be noted, however, that the decrease in stock volume with decreasing modularization level is due to the option of expressing it in cubic metres to evaluate the storage space occupation. Thus, although the amount of materials used increases as the level of modularization drops (due to the need to ensure greater onsite safety stock as a result of the greater unpredictability, probability of defects, and waste of the uncontrolled working environment), the storage of volumetric units significantly increases the occupation of storage space.

In terms of **time performance (R1.2)**, the most relevant metrics to compare are the customer order fulfilment cycle time and the contractual project schedule by analysing the conformance ratio results. In this regard, modular scenario III is the only one that meets the contractual time, taking the defined planning assumptions. Also, there are no significant differences in project completion dates of scenarios I and II.

Regarding **financial performance (R2)**, the three modular scenarios meet the contractual budget — project conformance ratios under 100%. However, scenario III outperforms the others, with a lower percentage of total operation and maintenance costs in the project budget. When scenarios I and II are compared, the first one performs better as the lower complexity of the prefabricated units leads to lower engineering and equipment costs, and the smaller size results in lower onsite handling costs since no auxiliary material is required to develop/acquire and fewer transports are scheduled, in addition to eliminating the need for external storage space renting, despite the higher materials, labour, and site work costs.

As offsite activity occurs in a controlled environment, scenario III performs better in terms of **quality (R3)**. However, it is estimated that non-conformities occur during transport due to the possibility of damage to home appliances during the transport route, which does not happen in the other cases. Thus, it may be worthwhile to investigate another scenario corresponding to the prefabrication of a volumetric unit, with all finishing elements except for the home appliances, to evaluate if it results in better overall performance[12].

Moreover, as the majority of the defects in the production of the volumetric units of scenario II are detected in the two-dimensional elements, its quality performance is not significantly different from scenario I.

Considering the overall **safety performance (R4.1)**, it can be argued that developing the majority of the construction work offsite leads to more satisfying results. Despite the higher weight of materials, which requires more careful onsite handling and lifting due to the risk inherent in dropping such an enormous volume, scenario III results in lower frequency and severity of estimated occupational accidents, as well as lower values of operations requiring special PPE and involving critical postures with ergonomic risk.

Since the onsite work is nearly equal in scenarios I and II, the results do not differ significantly. Both show a low severity level of more frequent occupational accidents, explained by the onsite lower occupational safety control. However, although scenario I requires more onsite effort, deal with lighter modules contributes to slightly better safety results. Thus, if a company lacks the necessary capacity to develop solutions to ensure safe onsite handling of heavy modules, the prefabrication of two-dimensional units may be considered.

Finally, in terms of **environmental sustainability performance (R4.2)**, the analysis of the defined indicators reveals that, apparently, scenario III stands out with lower consumption of energy and materials, lower generated waste, and higher percentages of materials diverted from disposal for recycling and reuse, owing to the fact that the project is completed in less time, with a higher percentage of work done in a controlled environment. Once more, there are no significant differences between scenarios I and II.

Based on these findings, the targeted 75% modularization appears to have the best overall performance. However, to draw more appropriate conclusions for the company's strategic goals, it is suggested that a multi-criteria model tailored to its operation strategy be developed in conjunction with the proposed framework.

Furthermore, if scenario III is discarded for any reason external to the framework analysis, a more detailed analysis of scenarios I and II should be performed, keeping in mind the company's strategic context and the construction project's objectives.

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[12] This analysis could also be interesting for evaluating questions about the warranty of home appliances.

5 Conclusions, limitations and future research

Industrialization techniques are increasingly being used by construction companies to increase productivity, improve product quality, and gain a competitive advantage. However, they still have great uncertainty about how industrialization and modularity concepts may be applied to building projects to realise benefits across all supply chain segments. This research project is an attempt to begin bridging the gap.

This chapter presents the research findings, considering the project's objectives, reveals its main limitations and suggests further research.

5.1 Research objectives and contributions

The primary goal of this study was to fill a research gap in decision-making about the optimal level of modularization via construction supply chain performance evaluation. To that purpose, the conducted research attempted to address the defined research questions by attaining the project's objectives.

Considering the objective of *identifying critical factors that influence the implementation and execution of industrialized construction projects*, this research contributes with a SLR of previous studies on the CI field.

To *define an effective strategy for designing different levels of modularization within a building unit*, this study proposes using a product architecture modularity approach already tested in the automotive industry, where modularization concepts have been successfully explored. The suggested methodology enables the determination of the ideal degree of detailed description of construction components, which serves as the foundation for designing various levels of modularization within a building unit.

Given the context of the decision-making process about the ideal level of modularization, the *definition of a suitable supply chain performance evaluation system*, it is proposed a balanced integrated assessment approach based on the revision of the EFQM Excellence Model, Balanced Scorecards, and SCOR methods.

As a result, this study aims to contribute to the CI literature with a *conceptual framework for assessing supply chain performance which aids to determine the ideal level of modularization for a construction project*, that has been *validated* with semi-structured interviews with construction experts and a case study on a MiC project development context.

5.2 Research findings discussion

Given this, an overall discussion of the investigation results is presented to support the subsequent research conclusions and the proposed future research.

Considering the semi-structured interviews and case study results, it can be argued that the proposed framework has high reliability and applicability. On the one hand, it is clear that, at its current maturity and robustness level, the proposed framework implementation is capable of producing clear results that can aid in the comparison of different construction scenarios' performance evaluation. In this sense, conclusions on the optimal level of modularization to apply to a construction project can be drawn, with the produced results aligning with the company's strategic context. On the other hand, in order to produce more robust results, the framework requires additional research. In fact, following the implementation of the case study, the framework structure and the produced results were reviewed with the construction experts involved in the project, and the discussion topics were as follows.

1. Framework implementation process: All construction experts involved in this project agreed that the evaluation procedure had been comprehensively developed;
2. Ideal granularity level definition: The construction experts were thrilled with this analysis method. The company's head of BIM officer proposed an internal study of the integration of component interactions analysis in DSM format on BIM output when designing a CI project to aid granularity analysis. However, given the previously mentioned possibility of developing different cladogram analyses based on different detailed levels of construction projects, the company should first determine the intended standard level of detailed description before implementing this framework.
3. Evaluation factors and indicators: Following the implementation of the case study, the majority of experts agreed that the evaluation factors and indicators included to assess each framework dimension are adequate to cover the key aspects of CI projects in the "project requirements", "enablers", and "results" phases. Some experts, however, suggested that more criteria may be required in some specific, more complex cases that were not identified. Thus, the proposed structure should be regarded as a generic open template. Any user can customise it for specific projects by adding new criteria or removing existing ones, enhancing innovation and framework development;
4. Factors and indicators assessment: Although clear conclusions must be drawn regarding the robustness of this framework, it is agreed that more consistent results could be obtained if weights

were assigned to factor analysis based on their impact on MiC project implementation. Furthermore, rather than relying on checklists for "project requirements" and "enablers" analysis, each factor should be quantified and assigned a maturity level (e.g., 1–5). As a result, decisions on these phases should be based on a weighted value that takes these two factors into account. In addition, more research into how to define a standard way to evaluate each factor should be conducted in order to produce consistent results through different project analyses;

5. Unit of analysis: Although the selected unit of analysis in the case study was two room divisions, the experts believe that the suggested framework could be used to analyse more complex units (e.g., a complete building constructed through a fully MiC approach).

Furthermore, it is acknowledged that the findings of this research could be more significant if: (1) more construction experts from various AEC fields and companies (or academic institutions) were involved in this investigation; (2) historical data was available to base the "results" phase analysis; (3) maturity models' literature findings were included for the evaluation factors assessment; and (4) a consistent weighted multi-criteria overall analysis was developed to compare the construction scenarios.

5.3 Research limitations

As a result, some limitations of this study are worth noting.

First, the SLR concerns the inclusion of articles based solely on "Title" field keywords, considering the project timeline and the primary purpose. Recognising just papers with modularization and industrialised building concepts in their titles, there is a risk of excluding studies that could also contribute to this research.

Second, the literature-based framework validation might be biased since the construction experts involved belong to the same construction firm. Semi-structured interviews could have generated stronger results if professionals from diverse AEC companies and academic institutions had participated in this study.

Third, although the case study provides empirical validation, no systematic implementation method for the proposed framework or factors' evaluation is defined. To aid in the application of the framework, a structured factor evaluation system might be established.

Finally, to offer a comprehensive output, the framework should have been supplemented with a consistent method to aid in select the ideal level of modularization based on the strategic context of the user.

5.4 Future research

By combining the research contributions and limitations, future research is recommended.

First, future research should look into developing a systematic implementation methodology that adopts standardised methods to assess each evaluation dimension, factor, and indicator. Furthermore, future research studies are invited to further investigate the inclusion of a maturity level analysis to assess the proposed evaluation factors and indicators. Finally, another proposal is to create a weighted multi-criteria evaluation technique to assist the final decision at the ideal level of modularization, as not all of the included aspects have the same impact on the decision.

To achieve these future objectives, an in-depth study on modularization business case analysis with numerous case projects is recommended, in addition to a more comprehensive literature analysis, to collect best practises and critical success factors for modularization business case analysis.

Finally, it should be noted that, as previously stated, the proposed version of the conceptual framework must not be static and may be adapted to the construction context in which the users are inserted, for instance, by including additional evaluation items important for a specific project decision.

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Appendixes

A References in the systematic literature review

Table A.1. Articles included in the review.

No.	Author(s)	Paper title	Year
1	Loo and Wong	Towards a Conceptual Framework of Using Technology to Support Smart Construction: The Case of Modular Integrated Construction (MiC)	2023
2	Ali et al.	Modelling the relationship between modular construction adoption and critical success factors for residential projects in developing countries	2023
3	Tsz Wai et al.	A critical analysis of benefits and challenges of implementing modular integrated construction	2023
4	Arshad and Zayed	Critical influencing factors of supply chain management for modular integrated construction	2022
5	Abdul Nabi and El-Adaway	A Proactive Risk Assessment Framework to Maximize Schedule Benefits of Modularization in Construction Projects	2022
6	Wuni et al.	Four-pronged decision support framework for implementing industrialized construction projects	2022
7	Wuni et al.	Computing the severity of critical onsite assembly risk factors for modular integrated construction projects	2022
8	Wuni and Shen	Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong	2022
9	Wuni et al.	Quantitative evaluation and ranking of the critical success factors for modular integrated construction projects	2022
10	Wuni et al.	Critical risk factors in the application of modular integrated construction: a systematic review	2022
11	Wuni and Shen	Critical success factors for modular integrated construction projects: a review	2020
12	Wuni and Shen	Fuzzy modelling of the critical failure factors for modular integrated construction projects	2020
13	Hammad et al.	Building information modelling-based framework to contrast conventional and modular construction methods through selected sustainability factors	2019
14	Enshassi et al.	Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects	2019
15	Wuni and Shen	Holistic review and conceptual framework for the drivers of offsite construction: A total interpretive structural modelling approach	2019
16	Sharafi et al.	Identification of Factors and Decision Analysis of the Level of Modularization in Building Construction	2018
17	O'Connor et al.	Critical success factors and enablers for optimum and maximum industrial modularization	2014

Cont.

No.	Author(s)	Paper title	Year
18	Y. Zhang et al.	Key Performance Indicators of Offsite Construction Supply Chains: A Review	2021
19	Kamali et al.	Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices	2018
20	Kamali and Hewage	Development of performance criteria for sustainability evaluation of modular versus conventional construction methods	2017
21	Kamali and Hewage	Sustainability performance assessment: A life cycle based framework for modular buildings	2017
22	Çelik et al.	The performance evaluation of the modular design of hybrid wall with surface heating and cooling system	2016

Table A.2. References identification for each factor.

Code	References	Code	References
D1	**Project requirements**	**D6**	**Process efficiency**
1.1	[6], [11], [12], [15], [17]	6.1	[2], [3], [5], [14], [18]
1.2	[4], [14]	6.2	[16]
1.3	[6], [10] ,[15]	6.3	[9], [14] ,[15], [18], [22]
1.4	[6]	6.4	[14]
1.5	[5], [8], [15]	**D7**	**Time performance**
1.6	[5]	7.1	[1], [2], [4], [6], [7], [14]
1.7	[5], [10]	7.2	[9], [11], [13], [16], [17]
1.8	[2],[8], [9], [10], [15], [17]	7.3	[6], [9], [13], [14], [15], [17]
D2	**Culture and leadership**	7.4	[5], [14], [15], [19], [20], [21]
2.1	[15]	7.5	[18]
2.2	[15], [17]	7.6	[3], [6], [149, [15], [19], [20], [21], [22]
2.3	[6], [9], [11], [12]	7.7	[5], [7], [11]
2.4	[2], [3], [3], [4], [5], [6], [8], [9], [10], [11], [12], [13], [15], [17]	7.8	[4], [7], [10], [17], [18]
2.5	[2], [3], [6], [8], [9], [11], [12], [15]	7.9	[5] ,[11], [18]
2.6	[2] ,[4], [5], [6], [8], [9], [10], [11], [12], [19], [20], [21]	7.10	[13], [18]
2.7	[5]	**D8**	**Cost performance**
2.8	[9], [11], [15]	8.1	[4]
D3	**Planning and control**	8.2	[5], [19]
D3.1	**Offsite capacity**	8.3	[3], [9], [13], [14], [17]
3.1.1	[1], [5], [6], [9], [10], [11], [12], [14], [15], [18]	8.4	[5], [14], [19]
3.1.2	[4], [5], [7], [10], [17]	8.5	[3], [5], [10], [15]
3.1.3	[3], [14]	8.6	[5]
3.1.4	[4], [6], [14], [18]	8.7	[5], [6], [14], [18]
3.1.5	[3], [14]	8.8	[5], [18]
3.1.6	[3]	8.9	[5], [18]
D3.2	**Location and site attributes**	8.10	[5], [18]
3.2.1	[3], [6]	8.11	[1], [6
3.2.2	[14]	8.12	[3], [6], [14], [18], [19], [20], [21]
3.2.3	[3], [5], [6], [7], [8], [11], [12], [15], [18]	**D9**	**Quality performance**
3.2.4	[4], [6], [14]	9.1	[3], [14]
D3.3	**Onsite activities**	9.2	[4], [10], [12], [18]
3.3.1	[1], [5], [6], [9], [10], [11], [12], [14], [15], [18]	9.3	[2], [5], [6], [13], [14], [15]
3.3.2	[3], [15]	9.4	[5], [6], [14], [15], [22]
3.3.3	[5]	**D10**	**Safety performance**
3.3.4	[4], [6], [9], [18]	10.1	[19]
D3.4	**Transportation aspects**	10.2	[1], [3], [5], [13]
3.4.1	[3], [4], [7]	10.3	[5], [14]
3.4.2	[2], [3], [4], [5], [6], [9], [10], [11], [12], [14], [17]	10.4	[4], [5], [6], [10], [13], [14], [15]
D4	**Supply chain coordination**	10.5	[2], [4], [6], [14], [15], [19]
4.1	[3], [6]	**D11**	**Environmental sustainability performance**
4.2	[3], [6]	11.1	[1], [14]
4.3	[2], [3], [4], [7], [8], [9], [10], [11], [12]	11.2	[5], [6], [14], [15]
4.4	[4], [7], [11], [12]	11.3	[14], [16], [19], [20], [21]
4.5	[4], [10]	11.4	[5], [19], [20], [21]
4.6	[2], [4] ,[5], [8], [9], [11], [12], [16]	11.5	[5], [14], [16], [19], [20], [21]
4.7	[4], [7], [8]	11.6	[1], [6], [14], [15], [19], [20], [21]
D5	**Modelling Technology**	11.7	[19], [20], [21]
5.1	[9], [11], [12]	11.8	[14], [15]
5.2	[8], [12]	11.9	[2], [4], [15], [16], [19], [20], [21]
5.3	[4], [5], [6], [8], [9], [14]	11.10	[1], [2], [4], [5], [15], [16], [18], [22]
D12	**Module design considerations**		
12.1	[9], [11]	12.4	[9], [11], [12]
12.2	[2]	12.5	[11]
12.3	[2], [6], [7], [17]		

B Framework validation – interviews

The conducted face-to-face semi-structured interviews stem from the goal of adapting the initial draft of the literature-based framework to the practical context in which it should be applied.

The protocol for the study is presented in this appendix, with an emphasis on the main goals, data collection techniques, and the information processing approach. Finally, the study's outcomes are summarised.

It is acknowledged that the fact that every participant in this study is a part of the same construction company poses a limitation. Even though experts from different fields of expertise (AEC) have been included, the conclusions may have been biased by the coincident operating context. This study output version of the suggested framework, however, should not be rigid and can be modified in terms of factor inclusion and the ways in which it is integrated into various industrialised construction environments.

B.1 Empirical research structuring

The empirical study was designed for comprehending how the literature-based framework could be adjusted to the practical environment of MiC projects decision-making process through an effective structure.

Purpose of the study

As described in Table 1 (section 1.3), five research elements are explored: "project context", "framework structure validation", "modular solutions' definition", "organization's CI capacity evaluation", and "results evaluation approach". To assess them and achieve the main goal, the following objectives are stated:

1. Validate the structure of the proposed framework – comprehend its practical applicability;
2. Identify which critical factors influence the implementation of MiC projects ("project requirements" and "enablers" phases) – given the proposed structure, define which factors must be assessed to identify what can be industrialized and comprehend the company industrialization potential;
3. Identify which metrics should be used to assess and compare the MiC projects performance ("results" phase) – given the proposed structure, define which results' metrics must be assessed.

B.2 Data collection strategies and information processing

Given the defined objectives and research elements, there were selected three strategies for data collection: semi-structured interviews (individual and focus groups) and direct observation of modules' production in dst group. This appendix focus on the development of the semi-structured interviews.

B.2.1 Survey sample

To obtain the most consistent results possible in the research context, it was attempted to involve experts responsible for the many phases of a MiC project, to combine multiple perspectives on the industrialization process requirements. In this regard, the interviews protocol was developed based on the following items:

- **Interviewees' selection criteria:** workers who are involved in decision-making or implementation of an industrialization process;
- **Analysis unit:** implementation of a MiC project;
- **Case:** company's ongoing MiC project;
- **Limitation:** Although it was tried to incorporate different perspectives, it was considered a convenience sampling[1].

Given this, 11 construction experts were selected to participate in this empirical study.

Sample characterization

To support the subsequent analysis, Table B.1 presents the sample of the construction experts who attended the study, according to the following characterization items.

- **Age:**]20, 30],]30, 40],]40, 50], >50;
- **Field of expertise:** Architecture, Engineering, Construction, Other;
- **Hierarchical level at the company:** Operational, Intermediate position (Architect, Construction Manager, Project Manager, Team Leader), Executive Board (Top management, Administration);
- **Years working at the current company:** <5,]5, 10],]10, 15],]15, 20], >20;
- **Years of experience in traditional construction:** <5,]5, 10],]10, 15],]15, 20], >20;
- **Years of experience in MiC:** <5,]5, 10],]10, 15],]15, 20], >20;
- **Level of responsibility in the MiC implementation project:** Decision-maker (on the strategy and direction of the industrialization process), MiC responsible (responsible for ensuring that the industrialization process is carried out), MiC project member;
- **Expertise level in MiC projects:** Beginner, Intermediate/Advanced, Expert.

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[1] In the context of this validation study, the participants were chosen from inside the construction company's environment due to the ease of contact and availability, considering the project development context. However, it is recognised that the selection can be biased and the sample is not representative (Taherdoost, 2016).

Table B.1. Interviewees list, according to characterization items.

Code	Age	Field of expertise	Hierarchical level	Years at company	Years of traditional construction	Years of MiC	Degree of responsibility in MiC projects	Expertise in MiC
HMC	]40, 50]	Engineering	Executive	]5, 10]	>20	<5	Decision-maker	Beginner
HPP	]40, 50]	Architecture	Executive	]5, 10]	>20	<5	Decision-maker	Intermediate/ Advanced
HA	]40, 50]	Architecture	Intermediate	<5	]15, 20]	]15, 20]	MiC responsible	Intermediate/ Advanced
HBIM	]30, 40]	Engineering	Intermediate	]10, 15]	]10,15]	<5	MiC project member	Intermediate/ Advanced
ProjM	]30, 40]	Engineering	Intermediate	]10, 15]	]10,15]	<5	MiC responsible	Intermediate/ Advanced
ProdM1	]30, 40]	Engineering	Intermediate	]5, 10]	]5, 10]	<5	MiC project member	Beginner
ProdM2	]20, 30]	Engineering	Intermediate	<5	<5	<5	MiC responsible	Beginner
CTL	]40, 50]	Construction	Operational	<5	>20	<5	MiC responsible	Beginner
LSCM	]30, 40]	Engineering	Intermediate	]5, 10]	]5, 10]	<5	MiC project member	Beginner
QM	]40, 50]	Engineering	Intermediate	]5, 10]	]5, 10]	<5	MiC project member	Beginner
SM	]40, 50]	Engineering	Intermediate	]15, 20]	]15, 20]	<5	MiC project member	Beginner

Thus, given the literature findings, semi-structured interviews with highly experienced experts were conducted to validate the defined framework structure, identify critical factors that influence the implementation of MiC projects and metrics to assess and compare their performance. The interviewees were chosen based on their previous experience with MiC and in the building business.

B.2.2 Study development

When developing the interviews' questions, each one was assigned to the expert whose daily job is most closely related to the problem under investigation. After assigning all the created questions, the experts who had the exact same questions for the interview were placed in a focus group to construct more consistent results, which were provided by sharing ideas about it.

Request for participation in the study

Each interviewee (or group of interviewees in the case of focus groups) received an email prior to the interview outlining the aim of the study and seeking a suitable date and time to conduct the interview.

This email contextualises the project within the scope of a master's thesis in Industrial Engineering and Management, developed with a focus on the MiC project currently underway at dst group, with the goal of developing a framework capable of assisting in decision-making about the most appropriate level of modularization for an industrialized project, based on supply chain performance.

Furthermore, each email provided a brief explanation of the suggested framework's established functionality and of its output. Finally, the objectives of the scheduled interview were outlined so that the interviewee could reflect on what was important to consider before being provided with the framework structure. This approach is thought to produce more consistent results for the adjustment of the framework's structure to the needs of those who deal with the problem to which the framework attempts to answer.

Pilot test of the interview script – for interviews

Piloting for interviews is essential for evaluating questions and gaining interviewing experience. As a result, it is a crucial stage in the empirical investigation (Majid et al., 2017).

Given the project context, the pilot test was carried out with the company's supervisor, the Project and Logistics Process Manager, with a PhD, with experience in previous projects based on conducting interviews with similar objectives. In this pilot, the following scripted questions were asked to test (1) if the questions are understandable; (2) if the duration of the interviews does not exceed 60 minutes; (3) if potential doubts occur; and (4) if there are pertinent questions that have not been explored.

Interviews protocol

Table B.2 summarises the validated questions, considering the defined research elements[2]. Tables B.3 to B.8 display the scripts for each interview, and, in Figure B.1, the questions are assign to each phase of the most recent version of the framework structure at the time the interviews were conducted[3].

Following each interview, the conclusions, as well as the framework factors and indicators developed based on the experts' responses, combined with the literature findings, were handed back to them and a second meeting was scheduled to validate the conclusions taken.

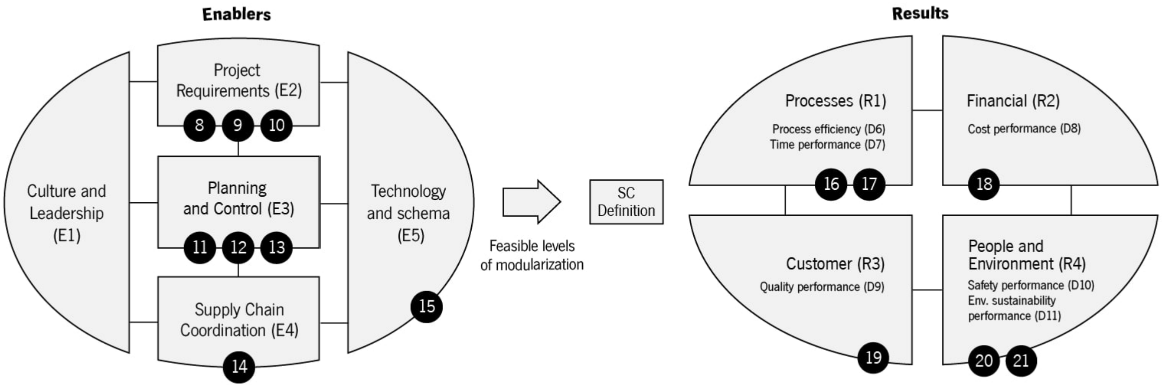

Figure B.1. Interview questions allocated to each framework phase (fist version produced).

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[2] ✓ indicates that a specific question was posed to a certain expert, and participants in several focus groups are highlighted in the same grey tone. Focus group 1 is composed by HMC, HA, HPP, and ProjM, focus group 2 is made up of ProdM1 and ProdM2, while focus group 3 is formed by QM and SM. The final focus group was established because they worked together on the MiC project, even though the questions assigned were not exactly the same.

[3] It was opted to not use interview questions to E1 category, as it could be biased by the culture of the company were the study was undertaken.

Table B.2. List of questions addressed to the interviewees.

Research elements (purpose)	No.	Question	Interviewees										
			HMC	HPP	HA	HBIM	ProjM	ProdM1	ProdM2	CTL	LSCM	QM	SM
Project context (Understand the relevance of the research topic)	1	What is your role in design and planning of the company's MiC projects?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Framework structure validation (Ensure the adjustment of the framework to the practical context of the design and planning processes of a construction project)		Proposed framework structure presentation, description of the development process and assumptions.											
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Modular solutions' definition (Identifying the factors that underpin the identification of structures with the potential to be industrialized)	8	How should a construction project be analysed to identify the potential for developing modular solutions?	✓	✓	✓		✓						
	9	What characteristics/requirements of construction projects are typically evaluated during the design stage?	✓	✓	✓		✓						
	10	What aspects enhance/condition the design of modular solutions when just the requirements of the construction project are considered (ignoring the company's CI capability)?	✓	✓	✓		✓						
Organization's CI capacity evaluation (Identification of factors that allow evaluation of the company's capacity to generate the industrialized solutions that it intends to develop)	11	Which elements must be considered when planning and controlling component production in the context of construction industrialization, taking into account the offsite capacity, site location and activity, and the required transport logistics?						✓	✓				
	12	Is there another planning and control sub-category that should be examined in addition to "Offsite capacity", "Location and site attributes", "Onsite activities" and "Transportation aspect"?						✓	✓				
	13	What elements related to building site characteristics and activity may influence potential off-site production scenarios?								✓			
	14	What issues/factors should be considered in modular construction logistics planning and supply chain coordination?						✓	✓		✓		
	15	Which factors regarding modular design standards and modelling technology can influence the creation and development of industrialized solutions?				✓							
Results evaluation approach (Identification of relevant factors for the evaluation and comparison of the performance of different development scenarios of a given MiC project)	16	What process efficiency indicators are important for analysing and comparing various modular construction scenarios?						✓	✓		✓		
	17	What time performance metrics are important for analysing and comparing various modular building scenarios?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	18	What cost performance metrics are important for analysing and comparing various modular building scenarios?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	19	What quality performance related indicators are important for analysing and comparing various modular construction scenarios?										✓	
	20	What safety performance indicators are important for analysing and comparing various modular construction scenarios?											✓
	21	What environmental sustainability performance indicators are important for analysing and comparing various modular construction scenarios?										✓	✓

Table B.3. Questions guide for interview 1 – Head of BIM.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation	Proposed framework structure presentation, description of the development process and assumptions.	
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Organization's CI capacity evaluation	8	Which factors regarding modular design standards and modelling technology can influence the creation and development of industrialized solutions?
Results evaluation approach	9	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	10	What cost performance metrics are important for analysing and comparing various modular construction scenarios?

Table B.4. Questions guide for interview 2 – Construction Team Leader.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation	Proposed framework structure presentation, description of the development process and assumptions.	
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Organization's CI capacity evaluation	8	What elements related to building site characteristics and activity may influence potential off-site production scenarios?
Results evaluation approach	9	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	10	What cost performance metrics are important for analysing and comparing various modular construction scenarios?

Table B.5. Questions guide for interview 3 – Logistics and Supply Chain Manager.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation		Proposed framework structure presentation, description of the development process and assumptions.
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Organization's CI capacity evaluation	8	What issues/factors should be considered in modular construction logistics planning and supply chain coordination?
Results evaluation approach	9	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	10	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	11	What cost performance metrics are important for analysing and comparing various modular construction scenarios?

Table B.6. Questions guide for focus group 1.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation		Proposed framework structure presentation, description of the development process and assumptions.
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Modular solutions' definition	8	How should a construction project be analysed to identify the potential for developing modular solutions?
	9	What characteristics/requirements of construction projects are typically evaluated during the design stage?
	10	What aspects enhance/condition the design of modular solutions when just the requirements of the construction project are considered (ignoring the company's CI capability)?
Results evaluation approach	11	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	12	What cost performance metrics are important for analysing and comparing various modular building scenarios?

Table B.7. Questions guide for focus group 2.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation		Proposed framework structure presentation, description of the development process and assumptions.
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Organization's CI capability evaluation	8	Which elements must be considered when planning and controlling component production in the context of construction industrialization, taking into account the offsite capacity, site location and activity, and the required transport logistics?
	9	Is there another planning and control sub-category that should be examined in addition to "Off-site capacity", "Location and site attributes", "Onsite activities" and "Transportation aspect"?
	10	What issues/factors should be considered in modular construction logistics planning and supply chain coordination?
Results evaluation approach	11	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	12	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	13	What cost performance metrics are important for analysing and comparing various modular construction scenarios?

Table B.8. Questions guide for focus group 3.

Research elements	No.	Question
Project context	1	What is your role in design and planning of the company's MiC projects?
	2	Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?
	3	Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?
Framework structure validation		Proposed framework structure presentation, description of the development process and assumptions.
	4	Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
	5	Do the analysis dimensions defined in each phase meet the needs of the project design process?
	6	Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
	7	Do you consider that the framework's structure can address the problems associated with designing modular construction projects?
Results evaluation approach	8	What time performance metrics are important for analysing and comparing various modular construction scenarios?
	9	What cost performance metrics are important for analysing and comparing various modular construction scenarios?
	10	What quality performance related indicators are important for analysing and comparing various modular construction scenarios?
	11	What safety performance indicators are important for analysing and comparing various modular construction scenarios?
	12	What environmental sustainability performance indicators are important for analysing and comparing various modular construction scenarios?

Example of an interview script

The interview script for the interview I (HBIM) is presented for showing the planned questions in the interview environment.

Part I – Interviewee characterization

At the beginning of the interview, it is handed a brief questionnaire for sample characterization, which contains the items mentioned in subsection B.2.1.

Part II – Validation of the framework structure and identification of critical factors

At an early stage of investigating modular construction options, it is crucial to acknowledge the benefits, challenges, and critical factors of this new construction paradigm. In this sense, the challenge of supply chain integration and management arises to benefit from the advantages in terms of time, cost, quality, safety, and sustainability while avoiding the design, planning, transport, and storage obstacles that distinguish modular construction from traditional construction. It should be noted that the supply chain includes all processes involved, from the selection of suppliers and subcontractors to delivery to the client (including manufacturing processes), which are influenced by decisions made in the project's design phase.

Within the context of the dst group's modular building projects and related supply chains,

1. What is your role in design and planning of the company's MiC projects?

Given the effort involved in the design phase of a modular construction project, as well as the significant impact that decisions made in this phase have on the overall orchestration, execution, and performance of the project supply chain, it is important to consider solutions that facilitate and assist this phase of the project, attempting to provide answers to the most relevant problems. In this manner,

2. Have the issues "what should be industrialized" and "to what extent should it be industrialized" ever arisen when designing a MiC project?

In this context, the idea of creating a framework capable of assisting decision-making regarding the most appropriate level of modularisation to meet construction requirements arose, taking into account the impact on the performance of the construction project supply chain and the company's strategic context.

3. Do you think it is important to create a tool that can assist in deciding on the most suitable level of modularization for a construction project based on the supply chain performance?

After reviewing the literature on critical factors in the implementation of modular construction projects and commonly used supply chain performance evaluation systems, it was realised that there are several factors that impact on different phases of the design process and supply chain. In this sense, it was decided to structure the proposed framework in three application phases:

(a) definition of possible modularization scenarios, based on construction project requirements;

(b) analysis of the company's CI capacity, considering organizational factors: Culture and Leadership, Planning and Control, Supply Chain Coordination, and Modelling Technology;

(c) and assessment of supply chain performance results associated with each of the scenarios under analysis, according to four categories: Processes, Financial, Time, Safety and Environmental sustainability performance.

Thus, by comparing the assessments of the many performance categories, the organisation utilising the framework should select the scenario that produces the outcomes that are most aligned with its strategic context—the level of modularization that is best suited to the project[4]. In this sense,

4. Do you consider the division of the analysis phases defined for the framework to be appropriate? If not, what could be improved?
5. Do the analysis dimensions defined in each phase meet the needs of the project design process?
6. Are there any essential aspects to consider while designing a modular construction project that the framework dimensions cannot address?
7. Do you consider that the framework's structure can address the problems associated with designing modular construction projects?

Considering the second implementation phase, regarding the definition of organization's CI capacity, in order to identify the factors that allow evaluation of the company's capacity to generate the industrialized solutions that it intends to develop.

8. Which factors regarding modular design standards and modelling technology can influence the creation and development of industrialized solutions?

Finally, considering the results evaluation approach proposed to the last section of the framework, regarding the modelling of modular construction projects,

9. What time performance metrics are important for analysing and comparing various modular construction scenarios?
10. What cost performance metrics are important for analysing and comparing various modular construction scenarios?

B.3 Empirical study results

This section summarises the interviewees' responses and presents the conclusions reached. Table B.9 outlines the answers to the defined questions, with the conclusions drawn by the interview (individual or focus group), to simplify the results presentation.

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[4] At this point, the proposed framework structure is presented to the interviewee.

Table B.9. Interviews' results.

Research element	No.	Interview 1 conclusions (HBIM)	Interview 2 conclusions (CTL)	Interview 3 conclusions (LSCM)	Focus group 1 conclusions (HMC, HPP, HA, ProjM)	Focus group 2 conclusions (ProdM1, ProdM2)	Focus group 3 conclusions (QM, SM)
Project context	1 - 3	Regardless of their role in MiC project design, all interviewees agreed that the main challenges when designing a project are defining the elements that should be industrialised and determining the most appropriate level of modularization. They agreed that supply chain performance evaluation is an interesting foundation for the intended analysis and supported the development of the proposed framework to provide answers to these problems.					
Framework structure validation	4	The proposed structure received no suggestions from the HBIM.	The proposed structure received no suggestions from the CTL.	The proposed structure received no suggestions from the LSCM.	The importance of examining project requirements as an independent first analysis phase was suggested. According to focus group 1 discussion, if it invalidates the project's modular potential, there is no point in assessing the company's CI capacity.	Focus group 2 emphasises that a company's ability to industrialize a construction project is more closely related to its ability to ensure an appropriate CI environment ("enablers" assessing) than to the project requirements, which should be evaluated first.	The proposed structure received no suggestions from focus group 3.
	5 - 7	HBIM proposed adjusting "technology and schema" to "modelling technology" to make this dimension more focused on modelling issues, as he believes it is a crucial component of CI.	Although some alterations to the framework phase organization were proposed, the remaining interviewees agreed that the defined dimensions are capable of addressing the most critical aspects of MiC project design that may influence the decision on the optimal level of modularization. Any other category was suggested.				
Modular solutions' definition	8	–	–	–	According to focus group 1, when assessing the modular potential of a building unit, it is crucial to include the "repeatability" and "standardization" of structures, materials, and finishes.	–	–
	9	–	–	–	Following the identification of recurring elements, the construction design phase is structured to assess the viability of incorporating prospective modular elements into the building structure while maintaining construction safety and stability.	–	–
	10	–	–	–	For focus group 1, the main limitations to MiC project development are the "client's receptivity" and, thus, the "design flexibility" to adapt certain features to meet the needs of a modular solution. Considering building stability, "building integration" and "assembly tolerances" must be included to assess the viability of some components' industrialization.	–	–

Cont.

Research element	No.	Interview 1 conclusions (HBIM)	Interview 2 conclusions (CTL)	Interview 3 conclusions (LSCM)	Focus group 1 conclusions (HMC, HPP, HA, ProjM)	Focus group 2 conclusions (ProdM1, ProdM2)	Focus group 3 conclusions (QM, SM)
Organization CI capacity evaluation	11	–	–	–	–	Focus group 2 note the inclusion of the assessment of the “capacity to produced at the required rate”, considering the needed offsite and onsite skilled workforce, materials, equipment, layout, storage capacity, and production planning, quality control, and transportation management teams and systems, as well as the site location. It is also crucial to include the evaluation of the ability to develop CI supportive, “cargo securing” and “onsite solutions to support modules installation”.	–
	12	–	–	–	–	Any other relevant sub-category was suggested.	–
	13	–	CTL focused on the site’s “location” and “accessibility” in light of legal work and supply restrictions, and unloading licences. He also noted the importance of having the necessary components and equipment available when needed, which implies efficient site management and control.	–	–	–	–
	14	–	–	LSCM emphasised the importance of establishing a supply chain with synchronised ability to develop modular solutions, which must be efficiently planned in an integrated manner to coordinate offsite and onsite work packages.	–	–	–
	15	HBIM believes that BIM, as a supporting technology, is critical to the definition of modularization. Also, to provide accurate design and engineering specifications, designers must be able to adjust the design for modularization and DfMA.	–	–	–	–	–

Cont.

Research element	No.	Interview 1 conclusions (HBIM)	Interview 2 conclusions (CTL)	Interview 3 conclusions (LSCM)	Focus group 1 conclusions (HMC, HPP, HA, ProjM)	Focus group 2 conclusions (ProdM1, ProdM2)	Focus group 3 conclusions (QM, SM)
Results evaluation approach	16	–	–	The logistical issues associated with the "number of orders shipped to site" were highlighted by the LSCM.	–	ProdM1 and ProdM2 emphasised the evaluation of the "prefabrication rate" and "number of employees required" to assess process efficiency while considering the "average labour occupancy rate".	–
	17	HBIM emphasises the BIM modelling time and associated prototyping time, as well as the productive and onsite assembly times, as they are related modelled elements and interfaces.	CTL prioritised site development time to prepare the building for the modules, productive and onsite assembly times, and time to unload modules onsite.	In terms of supply chain efficiency, LSCM concentrated on schedule construction activities and route shipment cycle times.	Focus group 1 discussed the contractual project schedule, project completion time, and prototyping cycle time.	Focus group 2 focused on offsite production metrics: activity schedule, productive time, downtime for quality tests and verification, rework, picking, packing, loading and unloading vehicles, and onsite assembly cycle times, given the industrialized elements.	Focus group 3 mentioned downtime for quality tests, verification, and rework, as well as the time required to schedule construction activities in terms of quality, safety, and environmental operations.
	18	HBIM referred the BIM modelling costs.	CTL concentrated on construction site costs (common site work-related costs), with an emphasis on onsite module unloading, handling, and installation.	LSCM emphasises the costs associated with SCM and transportation from the perspective of route optimisation.	Focus group 1 concentrated on the contractual project budget, total operation and maintenance costs, component engineering test costs, and the required initial cost.	Focus group 2 focused on labour, materials, and equipment costs, as well as materials management, transportation, storage space renting, and product indirect costs.	Focus group 3 focused on quality related and production indirect costs.
	19	–	–	–	–	–	QM highlighted the number of non-conformities found in finished products, emphasising the importance of controlling defects caused by transportation to assess the effectiveness of material resistance and cargo-securing solutions.
	20	–	–	–	–	–	Based on ILO approach, SM focused on the importance of controlling the frequency and severity of reported occupational accidents, as well as the number of activities requiring special PPE and implying critical postures with ergonomic risk.
	21	–	–	–	–	–	Focus group 3's most frequently mentioned environmental sustainability-related factors were the materials used and percentages of recycled and reused materials, as well as the generated waste volume, considering the percentages diverted from disposal to recycling or reuse.

Given the results of the interviews, it was possible to progress from the framework version based on literature findings to the final proposed structure. Figure B.2 depicts these two versions, highlighting the most significant changes as a result of this empirical study[5].

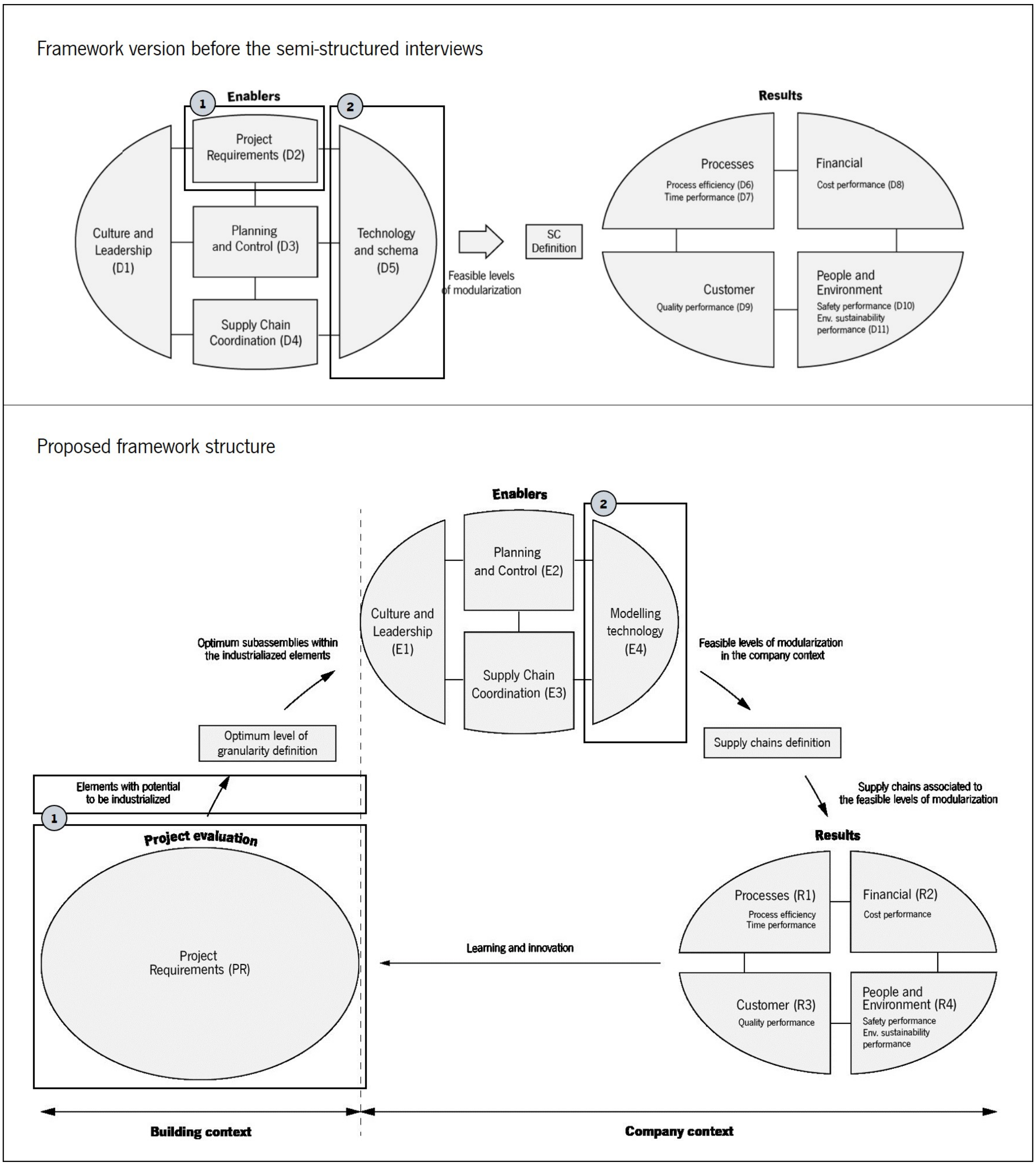

Figure B.2. First and final framework versions comparison.

Furthermore, referring to the research elements “organization’s CI capacity” and “results evaluation approach”, the conclusions drawn from the interviews are translated into the “enablers” factors and “results” metrics presented in Tables 16 and 17 of section 3.2.

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[5] It should be noted that the optimal granularity level definition step is not highlighted in this figure because it was a later change based on a subsequent literature review, module design, and production observation.

C “Enablers” factors analysis approach

In this appendix, Table C.1 summarises the analysis approach used to determine if the scenarios under consideration in the “enablers” evaluation phase of the case study meet each evaluation factor (of the evaluation categories E2, E3, and E4).

Table C.1. Analysis approach description for the factors in the ”enablers” categories E2, E3, and E4.

Code	**Enabler**	**Analysis approach**
E2	**Planning and Control**	
E2.1	**Offsite capacity**	
E2.1.1	Availability of skilled workforce	Verification of skilled workforce internal availability and/or subcontracting capability for cluster assembly and manufacture of the related components.
E2.1.2	Availability of required materials and production equipment	Internal analysis and market research of the viability of acquiring the required materials, equipment, solutions, and best practices to produce the clusters offsite.
E2.1.3	Ability to develop solutions to support CI	Survey of the suitable production system requirements and the capacity to invest in technology, for a further evaluation of the availability of internal expertise for projecting auxiliary solutions required for cluster production.
E2.1.4	Capability to produce at the required rate	Evaluation of the predicted production system’s capacity for producing each cluster at the required rate to meet the project’s schedule and quantities
E2.1.5	Capacity to ensure the required offsite storage capacity and an inventory control system	Determination of the required storage capacity for raw materials and intermediate and finished products, by comparing the expected input, production, and shipping rates for each cluster. Additional analysis of the internal capacity to manage offsite stock.
E2.1.6	Capability to develop an adequate production plant layout	Evaluation of the characteristics of the available area for implementing the prefabrication plant, as well as the investment capacity to adjust it to the production requirements of each cluster.
E2.1.7	Ability to ensure a production planning and management system	Analysis of the viability of using an existing, investing in, or developing a system for planning and scheduling production operations for the execution of each cluster .
E2.1.8	Ability to guarantee a quality control system	Analysis of the availability of the necessary resources to develop and execute a robust quality control plan for the clusters’ production and integration.
E2.1.9	Capacity to develop cargo securing solutions	Preliminary survey of the clusters stability and handling restrictions, for further verification of the internal capability to design and/or subcontract the creation of cargo security solutions without affecting product quality .
E2.2	**Location and site attributes**	
E2.2.1	Appropriate site location	Diagnosis of the geographical and demographic site conditions to analyse whether they fit the requirements for installing the clusters with the defined features.
E2.2.2	Required site accessibility	Study of the accessibility characteristics to determine whether the site can receive the trucks and cranes required to deliver and handle the clusters, taking into consideration the dimensions specified.
E2.2.3	Availability of licenses for site operations	Legal analysis of the site operating regulations and policy fulfilment, considering the required onsite activities for cluster installation.
E2.2.4	Suitable conditions to develop an adequate site layout	Analysis of site space constraints to verify if the necessary conditions are met to establish the layout that best suits the modules’ features and the related onsite activities.
E2.2.5	Availability of the required storage capacity onsite or in storing facilities close to the site	Investigation of available onsite storage space and/or the capacity to invest in nearby intermediate storage facilities, considering clusters size and onsite delivery and installation rates.
E2.2.6	Module unloading, lifting, and installation restrictions	Analysis of building’s height, crane lifting capability and radius, and onsite technical expertise to determine whether the clusters specs meet the site constraints.
E2.3	**Onsite activities**	
E2.3.1	Availability of skilled workforce	Analysis of skilled labour internal availability and/or subcontracting capacity for site preparation and module installation, ensuring MEP system and building’s integrity.
E2.3.2	Availability of the required components and equipment	Analysis of cluster production and onsite delivery rates to determine if the required components can be delivered when needed, followed by internal analysis and market research to determine the viability of acquiring the necessary equipment, solutions, and best practices for onsite activities, meeting onsite project requirements.
E2.3.3	Ability to develop onsite solutions to support module installation	Preliminary survey of cluster unloading, lifting, and movement restrictions, as well as equipment handling constraints, to confirm internal capability to design and/or subcontract the development of solutions to support onsite module installation without compromising product quality.
E2.3.4	Ability to manage onsite activity	Analysis of site preparation, installation operations, and the integration with offsite work, to assess internal capacity of forming a team and develop the required systems (or subcontract it) to manage onsite operation.
E2.3.5	Ability to manage and control onsite inventory	Analysis of internal capacity or the need for subcontracting a team to create and execute onsite stock management plans based on the optimum order quantity, considering production, delivery, and installation rates.

Cont.

Table C.1. Analysis approach description for the factors in the ”enablers” categories E2, E3, and E4 (Cont.).

E2.4	**Transportation aspect**	
E2.4.1	Availability of the most appropriate transport method with the required capacity	Analysis of the distance factory-site, as well as the capacity of the available modes of transportation, to determine whether there is any viable possibility of transporting the clusters while meeting the delivery deadline and ensuring product quality.
E2.4.2	Availability of an adjusted road network and infrastructures	Comparison of the weight and size of the clusters' transport loads with the infrastructure constraints between the plant and the construction site.
E2.4.3	Availability of the required transport permits	Analysis of the infrastructures' regulations to determine if the projected loads comply with the standard limits or if special load documentation is required, if there are traffic restrictions for the vehicles with defined dimensions, or cross-border checkpoints.
E2.4.4	Availability of a skilled transportation management and control team	Analysis of internal capacity and/or the need for subcontracting transport managers with technical expertise to deal with this modular scenario transportation issues.
E3	**Supply Chain Coordination**	
E3.1	Availability of fabricators and suppliers	Market research and contact with previous projects' suppliers to determine whether all necessary components can be delivered to the correct place at the right time.
E3.2	Adequate supply chain capability for CI	Awareness of the participants' (contractor, supplier, fabricator, etc.) capacity to deal with the logistical and product challenges of CI.
E3.3	Ability to ensure a supply chain integrated planning	Analysis of the internal availability and/or subcontracting capacity of experts with technical knowledge to coordinate and plan the supply chain associated with the construction scenario based on the defined clusters
E3.4	Ability to coordinate onsite and offsite work packages	Analysis of internal capacity to coordinate onsite and offsite activities, considering cluster characteristics, onsite assembly requirements and capacity, and rates of supply, production, delivery to site, and installation.
E3.5	Capacity to ensure an inventory management and control system	Analysis of internal capacity or the need for subcontracting the creation of an efficient stock management plan across the supply chain, considering storage spaces and rates of component supply, production, and installation.
E4	**Modelling Technology**	
E4.1	Presence of relevant supportive technology (BIM)	Verification of internal and/or subcontracting capacity for building project modelling based on the development of defined modules using BIM technology.
E4.2	Capability to adapt the design for modularization and DfMA	Analysis of the availability of internal knowledge for the design of clusters and their interfaces, capable of adapting the project from a DfMA perspective to this modularization scenario.
E4.3	Capability to provide accurate design and engineering specs	Analysis of the availability of internal expertise to design manufacturing drawings and documentation with the necessary specifications for the production and assembly of the defined clusters.

D Project scheduling for case study scenarios

This appendix's content is intended to clarify the time performance results (R2) reported in subsection 4.2.5. Some explanations for the presented values are provided in addition to the presentation of the Microsoft Project output for the modular scenarios under investigation.

Firstly, it is important to note that all the assumptions made have the observed values for the actual building project as a foundation, which approximates the 75% modularization scenario. As such, time performance results for 25% and 30% modularization scenarios are fictitious data based on the time of the activities that change from offsite to onsite development and the complexity of the produced units.

Since the complexity of offsite-produced modules is predicted to decrease from scenario III to scenario I, the time required to schedule construction activities (R1.2.5) is also expected to decrease progressively from scenario III to scenario I. The number of employees in charge of each operation, the availability of space, and the layout of the manufacturing plant structure, as well as the required components and operations for the development of the offsite activities assigned to each scenario, are all taken into account for this estimation process, resulting in the estimated durations presented in Table 25 for each scenario.

To schedule the expected throughput time for each scenario, some additional presumptions were considered. Beginning with the productive time (R1.2.8), ignoring production breaks related with quality issues, for all modular scenarios, the estimates are based on the following considerations:

- Before the beginning of the continuous manufacturing process, it is planned to prepare the MEP system single components over 10 t.u.: 5 t.u. for creating security stock and 5 t.u. to produce the elements required for the production of the first modules to be shipped;
- After the first 5 t.u., it is planned to start the two-dimensional MEP system elements, equally working 5 t.u. for stock and 5 t.u. to generate the needed parts to start the modules manufacture;
- Following that, the first produced modules of scenario I are ready to be picked, whilst for scenarios II and III, considering the projected production system, 1 and 4 t.u. of production activities, respectively, are required for the first modules to be completely manufactured;
- Then, the production of the units specified for each scenario takes 99,7 t.u. considering the total modules and the daily production of each scenario.

Furthermore, in this case study, the downtime for quality tests (R.1.2.9) is null for all scenarios. Although for scenario III, one quality test prohibits parallel activities, the logistics and management team projected it to be done outside the system line. For the remaining scenarios, no quality tests that require downtime are planned. Additionally, to determine the expected time for rework and re-inspection, as there is no previous data, real data on the project execution is used to base the presented fictitious values. In scenario III, 13 t.u. are defined for eventual breaks during productive time, whereas in scenarios I and II, approximately half of this value is expected. The same value is presented for these two scenarios because the majority of the defects detected in the volumetric structure produced in the second scenario might be due to defects in the two-dimensional elements, which correspond to the modules of scenario I.

As these two predicted time elements cannot be scheduled in the project Gantt chart of each scenario – since they are unpredictable –, although they should be considered to schedule the subsequent activities and estimate the project completion date, the activities related to R1.2.11, R1.2.12, and R1.2.14 are scheduled considering the expected end of throughput time (R1.2.8 + R1.2.9 + R1.2.10). For instance, in scenario III, as the picking activity occurs after the ending of the daily production, the last picking task is scheduled to start after the scheduled throughput time; as the aim is to pick all the produced modules each day, all the planned picking tasks are scheduled each working day till this date. However, it is recognised that it must be adjusted due the 13 expected added t.u. for rework activities, that do not occur sequentially in the beginning of throughput time as it could be perceived from the presented Gantt charts.

Figures D.1 and D.2 are presented to aid the comprehension of R1.2.11 and R1.2.12 times scheduling for scenarios II and III, respectively, considering a set of 6 modules. Any explanation is needed for scenario I, as only module cleaning is considered and it is scheduled sequentially on the daily produced modules. The t.u. are not revealed due to confidentiality.

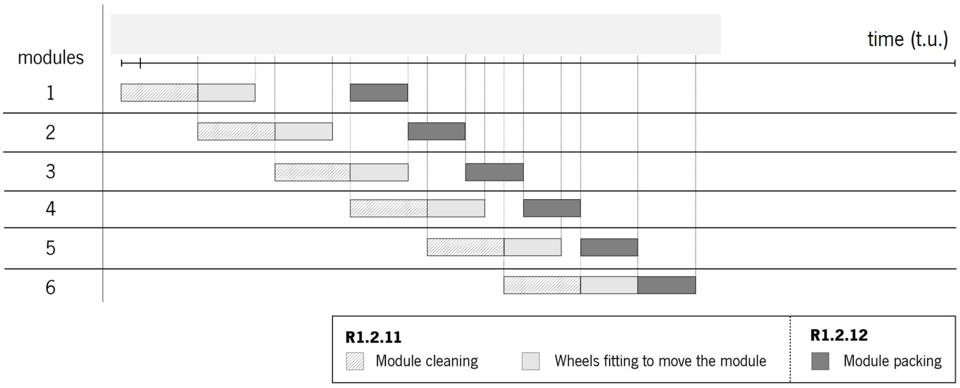

Figure D.1. Picking and packing product activities scheduling, for a 30% modularization scenario.

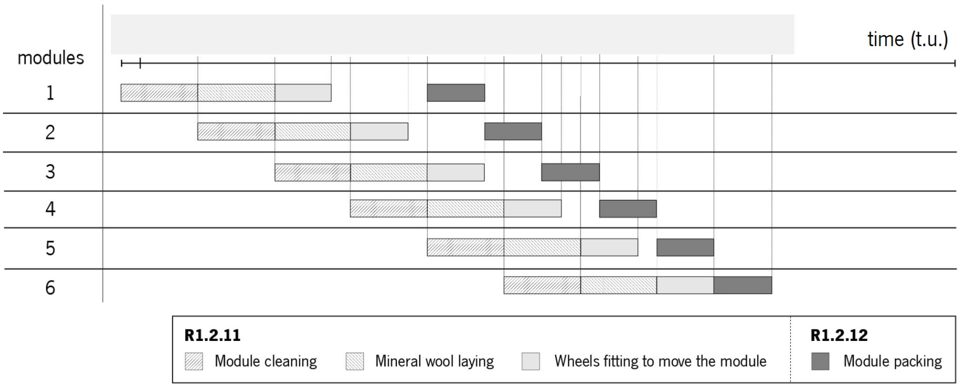

Figure D.2. Picking and packing product activities scheduling, for a 75% modularization scenario.

As shown, picking related tasks occur sequentially for each module, and each operation is done in continuum until it is completed for all the modules. To optimize the labour occupancy rate, packing is projected to occur sequentially for all the modules, taking the end of the last picking task as reference.

Although load vehicle cycle time (R1.2.13) is the same regardless of shipment origin and destination, considering the same loading team and vehicle capacity, the number of vehicles loaded for routes from manufacturing plant to storage facility and construction site, and from storage facility to construction site are specified to determine when this recurring task must be scheduled. Furthermore, just one vehicle per day was considered for each route. For scenarios II and III, when the storage capacity of the manufacturing plant is completed, the modules manufactured each day are carried to the storage facility at the start of the next day (till t.u. 238, for scenario II, and t.u. 248, for scenario III). For scenario I, load vehicle is only scheduled when the building site is estimated to be ready for receiving the modules. Following the completion of all module fabrication, there are scheduled load vehicle operations to the construction site (from manufacturing and storage plants). While scenario III has this operation scheduled every day until all modules are handed over, for scenarios I and II, it is only considered every two days due to the lower capacity of the more overburdened onsite workforce (since the same number of employees are assigned to offsite development of the same operations).

For route shipments cycle time (R1.2.14), two separate times are offered for scenarios II and III, considering the two destination point of route shipments: (1) the construction site and (2) the storage facility (intermediary shipments). Once again, this approach is not required for scenario I, as there is no need for external storage. In fact, when the storage capacity of the manufacturing plant was completed, the modules manufactured each day are carried to the storage facility at the start of the next day (till t.u. 238, for scenario II, and t.u. 248, for scenario III). After the fabrication of all the units is completed, it is scheduled a transport every 2 days, for scenario II, and a transport per day, for scenario III, in the next day of loading vehicle (the truck is loaded in one day and it goes to the distribution centre of the company in charge of transportation to set off for the construction site the next morning).

When a vehicle arrives on-site, a truck unload operation (R1.2.15) is scheduled, and onsite assembly (R1.2.16) begins. This value accounts for the time required to install the received modules on the appropriate building floor considering the operations required to functionally complete the toilet and kitchenette divisions. The scheduled time for scenario III corresponds to 1 t.u. to complete the activities required for the modules received, whereas for scenarios I and II, in addition to this, the time required to perform the operations that pass from offsite to onsite development in each scenario is increased by 30%[1].

Given these assumptions, Figures D.3, D.4, and D.5 display the time performance indicators results for 25%, 30%, and 75% modularization scenarios, respectively. The Microsoft Project output has been manipulated to conceal confidential data about project duration.

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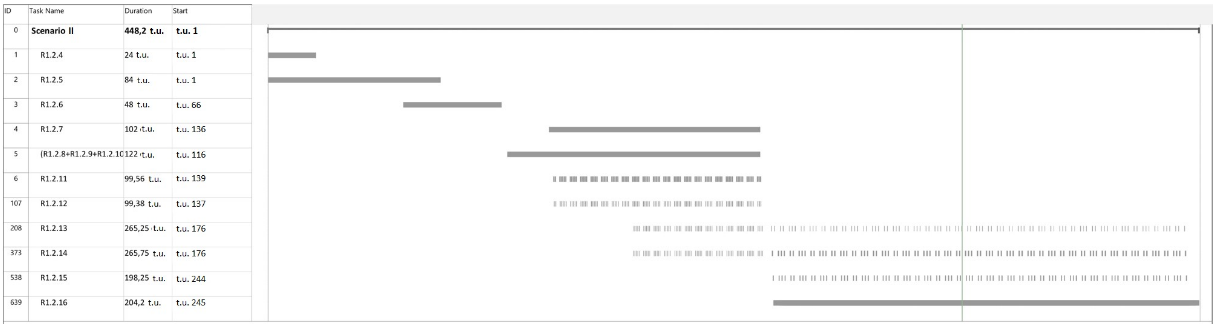
[1] This percentage was estimated by a construction expert working on the company where the case study was carried.

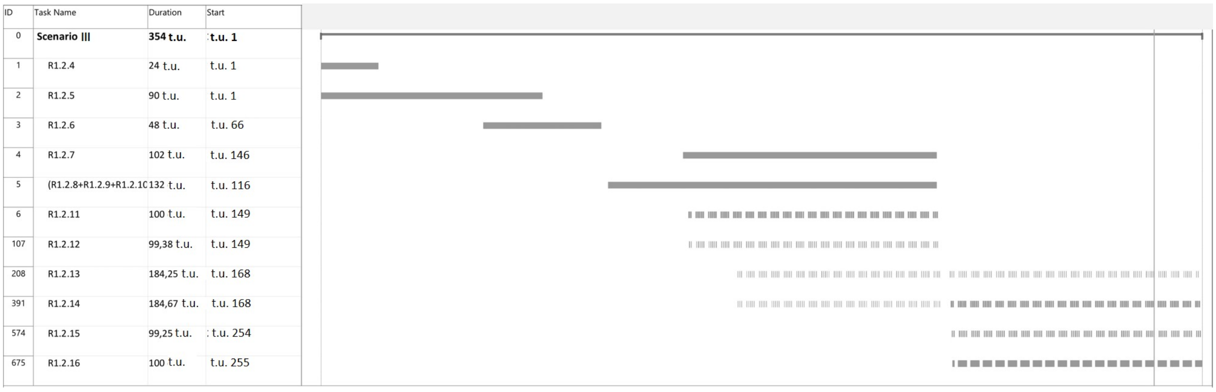
ID	Task Name	Duration	Start
0	**Scenario I**	**449,5 t.u.**	**t.u. 1**
1	R1.2.4	24 t.u.	t.u. 1
2	R1.2.5	78 t.u.	t.u. 1
3	R1.2.6	48 t.u.	t.u. 66
4	R1.2.7	102 t.u.	t.u. 135
5	(R1.2.8+R1.2.9+R1.2.10	121 t.u.	t.u. 116
6	R1.2.11	99,17 t.u.	t.u. 138
107	R1.2.12	99,56 t.u.	t.u. 138
208	R1.2.13	198,25 t.u.	t.u. 242
309	R1.2.14	198,63 t.u.	t.u. 243
410	R1.2.15	198,25 t.u.	t.u. 243
511	R1.2.16	205,5 t.u.	t.u. 245

Figure D.3. Project scheduling output for a 25% modularization scenario.



ID	Task Name	Duration	Start
0	**Scenario II**	**448,2 t.u.**	**t.u. 1**
1	R1.2.4	24 t.u.	t.u. 1
2	R1.2.5	84 t.u.	t.u. 1
3	R1.2.6	48 t.u.	t.u. 66
4	R1.2.7	102 t.u.	t.u. 136
5	(R1.2.8+R1.2.9+R1.2.10	122 t.u.	t.u. 116
6	R1.2.11	99,56 t.u.	t.u. 139
107	R1.2.12	99,38 t.u.	t.u. 137
208	R1.2.13	265,25 t.u.	t.u. 176
373	R1.2.14	265,75 t.u.	t.u. 176
538	R1.2.15	198,25 t.u.	t.u. 244
639	R1.2.16	204,2 t.u.	t.u. 245

Figure D.4. Project scheduling output for a 30% modularization scenario.



ID	Task Name	Duration	Start
0	**Scenario III**	**354 t.u.**	**t.u. 1**
1	R1.2.4	24 t.u.	t.u. 1
2	R1.2.5	90 t.u.	t.u. 1
3	R1.2.6	48 t.u.	t.u. 66
4	R1.2.7	102 t.u.	t.u. 146
5	(R1.2.8+R1.2.9+R1.2.10	132 t.u.	t.u. 116
6	R1.2.11	100 t.u.	t.u. 149
107	R1.2.12	99,38 t.u.	t.u. 149
208	R1.2.13	184,25 t.u.	t.u. 168
391	R1.2.14	184,67 t.u.	t.u. 168
574	R1.2.15	99,25 t.u.	t.u. 254
675	R1.2.16	100 t.u.	t.u. 255

Figure D.5. Project scheduling output for a 75% modularization scenario.