Master of Science (MSc.) Business Administration;
Entrepreneurship Innovation and Strategy, Master’s thesis

Prioritising Critical Success Factors of supply chain management in panelised construction, a case study

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25-6-2024

Acknowledgements
This thesis was written as the final component of the Master’s program in Business Administration with a specialisation in Entrepreneurship, Innovation, and Strategy at the University of Twente in Enschede. First, I would like to express my gratitude to Remco Siebelink and Louise Knight, my primary supervisors during this project. Although the supervisorship at first went differently than initially planned, your constructive feedback, particularly on the structuring of the thesis, has been invaluable in shaping this work. I am also grateful to Wilco Pelgröm, the internal supervisor at the case company, for granting me the freedom to conduct the research I envisioned and for providing essential contacts for the study. Additionally, I would like to thank all the interviewees from various firms for their time and effort. Finally, I thank my family and friends for their encouragement, which was crucial in completing this thesis, as well as for their understanding support and joyful distractions, which helped me relax and clear my mind during this research.

During the preparation of this work, I used generative AI in the following ways. Generative AI was used to generate potential synonyms for words to use in the paper. Generative AI was used as an exploration tool to get a first general understanding of key concepts within this paper. Generative AI was used to generate relevant search terms. Generative AI was used for grammar improving purposes. As author of this paper, I take full responsibility for the content.

Abstract

Moving construction projects from on-site to off-site using prefabrication techniques offers numerous potential benefits to society, including reduced build times and costs, enhanced control over built environments, and decreased risks associated with factory production and component traceability. However, transitioning work off-site introduces various implications, notably a fundamental shift in operational dynamics with an increased emphasis on design work. Additionally, the heightened customer involvement when using the off-site construction method known as panelised construction increases the complexity of these projects. This underscores the necessity for effective supply chain management in panelised construction. This research examined how effective supply chain management can be achieved in panelised construction by identifying and evaluating the Critical Success Factors (CSFs) as there were no existing CSFs specifically tailored to panelised construction. A literature review was conducted to identify CSFs from other off-site construction methods relevant to panelised construction. The transferability of CSFs to panelised construction is uncertain due to their distinctive structures, which give customers greater influence across various phases of the supply chain. These identified CSFs were assessed for relevance by a panel of experts and subsequently evaluated for importance by supply chain management experts from the case company's supply chain using the Analytical Hierarchy Process. Additionally, the expertise of these experts was assessed by the supra decisionmaker to give the experts with the highest expertise more influence on the prioritised list of CSFs. The study generated a prioritised list of CSFs specifically tailored to panelised construction, which were categorised across the five subcategories: forecast capacity, communication and collaboration, robustness, adaptability, and sustainability and yielded in total 21 factors. The list indicated which CSFs were of utmost importance in supply chain management for panelised construction. This, along with an analysis of why these CSFs are significant and an evaluation of the company's current supply chain management status, provided insights into the case company's level of supply chain management maturity and identified potential areas for enhancing performance. Contrary to what has been found in other types of off-site construction methods, where factors related to communication and collaboration were found to be most beneficial. This study indicates that although factors related to communication and collaboration are of high importance, factors related to adaptability are most important in panelised construction. The study suggests that effective supply chain management requires extensive communication and collaboration with external partners, involving critical stakeholders early and engaging key participants throughout the project. It also implies that in panelised construction, enhancing the supply chain's adaptability to changing conditions is crucial for its success.

Keywords: Supply chain management; Off-site construction; Panelised construction; Analytical Hierarchy Process; Complex façade systems; Critical Success Factors

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1 Introduction

Off-site construction, which is a hybrid of manufacturing and construction, has significant potential to address the construction industry their endemic problems, such as concerns related to quality and safety, delays and exceeding budgetary limits, and low productivity levels (Arashpour et al., 2018). Off-site construction involves assembling prefabricated assemblies, modules, or components in a specialised facility. This manufacturing process brings together various materials to create parts for a final installation taking place at the project site (Antillón et al., 2014). The implementation of off-site construction could benefit society in several ways, e.g. reduced build times and costs, better controlled built environments, reduced risks through factory production, computing and traceability of components, etc (Taylor, 2009). However, moving work off-site has several implications. The entire process operates differently, with a greater emphasis on the design work. Clients need to be sure of their decisions, because fixing mistakes can be slower due to the earlier design freeze (Kazi et al., 2007). This raises the need for a proper management of the supply chain in off-site construction (Said, 2015). In the construction industry, the supply chain encompasses, from an organisational perspective, architectural planning, engineering design, materials manufacturing and delivery, subcontracting practices, facilities management, and operations. From a social standpoint, it forms a complex network of relationships involving different stakeholders (Wang et al., 2017). Over the past few years, there's been a growing emphasis among researchers on the importance of supply chain management in construction projects. This increased attention is fuelled by the rising complexity and scale of these projects. Effective supply chain management has the potential to boost project performance and minimise waste resulting from inefficient materials handling and control (Wang et al., 2017). To achieve both short-term business objectives and long-term competitive advantage, many authors emphasise the importance of enhancing construction supply chain performance (Dubois & Gadde, 2000; Murray, 2003; Riley & Clare-Brown, 2001). Badi & Murtagh (2019) highlighted the necessity for both detailed, subdomain specific and sector-generic research regarding supply chains in the construction sector. There are three primary types of off-site construction, including components structures, panelised structures, modular structures, and there exists a mix between those called hybrid structures (Boafo et al., 2016). Zaalouk et al. (2023) showed that the attention in the off-site construction supply chain management research has shifted towards modular and panelised construction practices.

Nevertheless, most of the research has been done on modular and precast construction methods, whereas the size of the panelised construction research is relatively small (Hussein et al., 2021; Zaalouk, 2023). In modular construction, modular volumetric structures are prefabricated. These standardised modules serve as either an entire or a partial unit. The construction is done by assembling these various modules (Pan et al., 2008). Panelised construction makes usage of prefabricated panelised structures, these could be elements like structural insulated panels and metal frame panels. Prefabricating these panels enhances the speed and convenience of delivering them to a construction site (Boafo et al., 2016).

This research is conducted at Metadecor, a company that uses panelised construction for the creation of complex façade systems. Metadecor specialises in the design and development of architectural products for a wide range of projects inside the AEC (Architecture, Engineering, Construction) sector. It has around 35 employees, and with its approach, it puts a strong emphasis on collaboration with architects and clients from the early stages of project conceptualisation. Metadecor's primary goal is to contribute to the creation of remarkable and complex façades, whether it's for new construction projects or revitalizing existing buildings. Metadecor offers a variety of products and services to help architects achieve distinctive façades. For their projects, they realise products from aluminium, steel, Corten, copper, stainless steel, brass, magnelis, aluminium composite, and glass. In addition to façades, Metadecor also extends its expertise to components like sunshades, fencing, and roof construction.

With the increasing adoption of off-site construction in their new assembly hall, Metadecor aims to capitalise on the benefits of panelised construction for creating complex façade systems. This raises the need for a proper management of the supply chain in off-site construction (Said, 2015). Due to the fact that the off-site construction supply chain yields a higher complexity and fragmentation compared to traditional construction (Wang et al., 2019). Metadecor aims to optimise their supply chain management to maintain a competitive edge and retain their position as a market leader in the sector. Nevertheless, the company does not know how to improve their supply chain management.

When an organisation aims to achieve a specific goal, numerous factors must be considered, leading to complexity in decision making and management processes. However, this complexity can be reduced by utilizing the CSF (Critical Success Factors) theory (Kannan, 2018). The CSFs were developed by Rockhart (1979) and defined as "The limited number of areas in which satisfactory results will ensure successful competitive performance for the individual, department, or organisation. CSFs are the few key areas where 'things must go right' for the business to flourish and for the managers goal to be attained". The approach has been applied to define CSFs within specific business processes, projects, and strategies (Cooper, 2009). Therefore, this approach could be utilised within Metadecor's supply chain management process to pinpoint the critical concepts that are of utmost importance. There are several benefits of using the CSFs approach. It enables management to focus on critical areas of the business and gain understanding of the priority areas within it. The method is also easy to understand, relevant, and helpful for managers, this makes them more committed and involved in CSF research. The method can also be modified in various ways to meet the needs of individual studies (Boynton & Zmud, 1984; Henderson et al., 1987; Peffers et al., 2003; Premkumar & King, 1994; Rockart, 1979).

Previous research has delved into the topic of the CSFs, determinants, and key factors of successful supply chain management and a resilient supply chain in off-site construction (Arshad & Zayed, 2022; Liu & Liu, 2023; Wuni & Shen, 2023; Zhang et al., 2023). Wuni et al (2023), has rated the significance of the critical success determinants of supply chain management in MiC (Modular integrated Construction). MiC is the highest degree of prefabrication. Approximately 80-90% of construction tasks are carried out off-site in a controlled manufacturing facility. This research suggested reconsidering the relative importance of the success determinants which were found in a specific context in this specific type of construction (Wuni & Shen, 2023).

Contrary to modular construction, where standardised practices dominate, due to the reason that standard modules are being assembled to create a unit (Bertram et al., 2019). Panelised construction typically employs distinctive structures, giving customers enhanced influence across various phases of the supply chain, particularly during the design stage. This categorises panelised construction as engineer-to-order, which is the highest level of client involvement in the design, manufacture, and assembly process (Montali et al., 2017). In an engineer-to-order product the specifications of the product are uncertain, as the customers requires a completely new product (Akinc & Meredith, 2015). Modular construction leans more towards the make-to-order strategy, where the client has less influence on the design of the end product (Robinson et al., 2011). In make-to-order manufacturing, the product design is already established at the time of order placement. This means that clients can only influence the manufacturing and assembly processes of the product (Hendry, 2010). The heightened customer involvement of panelised construction adds complexity to the supply chain, these projects often face low information availability among themselves, which leads to the lack of coordination among actors in the supply chain which impacts the supply chain performance (Cigolini et al., 2022; Hussein et al., 2021).

Due to the lack of research on the success factors of supply chain management in panelised construction, Metadecor faces challenges in determining which factors are necessary for establishing effective supply chain management. While there exist factors relevant to other forms of off-site construction, it remains uncertain whether these are directly applicable to panelised construction, particularly concerning Metadecor's specific supply chain. Metadecor's products boast extensive customisation, resulting in heightened product complexity. Consequently, this demands increased engagement from all supply chain stakeholders (Pero et al., 2015). Without a clear understanding of these success factors, a company risks inefficiencies regarding materials handling and control (Wang et al., 2017). Moreover, the organisation might miss chances to boost its competitive standing, as the case company is uncertain about the factors that are most crucial.

The study aims to identify CSFs for effective supply chain management in panelised construction within the AEC sector. It also seeks to prioritise these factors for complex façade manufacturers like Metadecor to inform the development of a targeted supply chain management strategy. By focusing on the panelised construction in the AEC sector, this research aims to provide insights that are tailored to this specific subdomain within the broader construction industry. This sector-specific approach recognises the unique dynamics, and requirements that may exist in the supply chain of panelised construction. This research focusses on examining the supply chain of panelised construction as a whole. Which encompasses the design stage, production stage, logistics stage, and on-site construction stage. The study concentrates on comprehensively analysing the supply chain, encompassing its four stages, taking into account the lack of coordination among these stages and the conflicting goals that may arise within the diverse segments of the supply chain (Hussein et al., 2021).

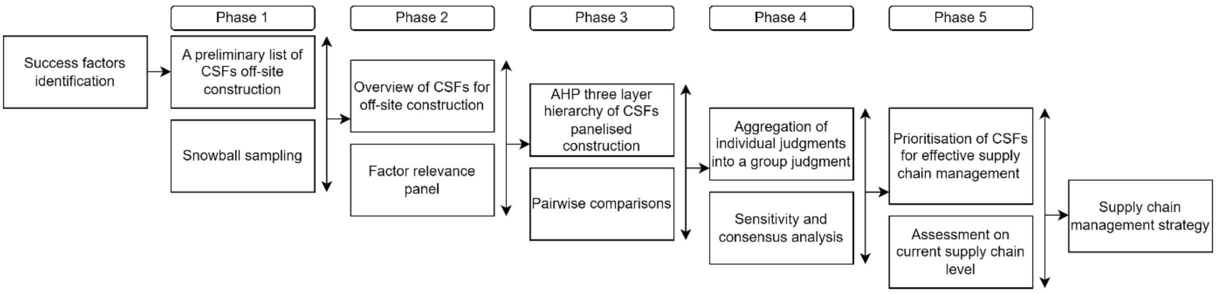
Based on the goal of this study, the central research question can be formed: 'How do CSFs regarding supply chain management contribute to achieving effective supply chain management in panelised construction for a complex façade system manufacturer?'

Moreover, four sub-research questions can be formulated to guide the project's progression and provide insights at various stages of the project. The sub-questions are the following:

1. What are the CSFs regarding supply chain management for off-site construction in the AEC sector, according to the existing literature?
2. What are relevant CSFs regarding supply chain management for a complex façade system manufacturer using panelised construction?
3. What is the overall prioritisation of importance of the CSFs of effective supply chain management for a complex façade system manufacturer?
4. To what extent could supply chain management be developed at the case company?

To address the research questions, a qualitative synthesis followed with a quantitative data analysis is undertaken. The process begins with a literature review aimed at identifying CSFs for off-site construction. This initial step creates a preliminary list of CSFs, which is refined using snowball sampling to create an overview of the CSFs for off-site construction. Thereafter, the list undergoes a relevance check to assess the transferability of the factors to panelised construction by the so-called 'factor relevance panel,' comprising both internal experts from the case company and external experts. This panel may contribute additional factors, which results in the three-layer hierarchy, needed for the prioritisation of the CSFs. The individual judgements from the prioritisations conducted by a designated panel are then aggregated. This is followed by a sensitivity and consensus analysis to validate the aggregation into a cohesive group judgement on the prioritisation of importance of the CSFs of effective supply chain management in panelised construction. The final step integrates the cohesive group judgment with insights from interviews and an assessment of the current supply chain level at the case

Figure 1. Research model.



Note. Own work

company, to establish a foundation for a strategic supply chain management plan. This process is depicted in Figure 1.

The outcome of this research enriches the existing literature on supply chain management in off-site construction by identifying the success factors specific to panelised construction and determining which factors of these are the most important at the case company's supply chain. Besides this, construction professionals involved in Metadecor's supply chain could refine their supply chain strategies by considering the factors identified in this specific context. Given the various stages considered in this research, stakeholders engaged at different points in the supply chain could derive valuable insights from this study. By prioritising the most important factors, Metadecor gets insights into the most crucial areas of their supply chain management, leading to greater efficiency regarding materials handling and control. Insights into the most important factors could also help Metadecor identify potential risks or vulnerabilities in their supply chain.

In Chapter 2, we explore the theoretical background, shedding light on relevant theories that underpin the research. These theories include off-site construction, encompassing structures made out of components, panelised structures, modular structures, and hybrid structures. Following this, we delve into complex façade systems. The discussion then extends to theories related to supply chain management, with a specific focus on the construction industry's supply chain, especially in the context of off-site construction. This chapter comes to a close with an examination of the theory surrounding the customer order decoupling point and a comparison between engineer-to-order design processes and their respective supply chains. Chapter 3 focuses on the methodology, where we discuss in detail the five phases of the research. Chapter 4 presents the findings, which will be discussed in chapter 5.

2 Theoretical background

In this chapter, we delve into theories directly relevant to our research. It will start with a comprehensive introduction to the construction industry.

The construction industry in the Netherlands accounts for around 4.67% of the Dutch gross domestic product as of 2021 (CBS, 2023). When looking from a more global perspective, the construction sector plays a pivotal role in the European economy. It not only directly contributes to approximately 6.16% of the average gross domestic product in Europe as of 2020 (UNECE, 2023). This industry also serves as a foundation for economic activities across various industries. The creation of economic value often occurs within or through the construction of buildings and other built assets. These constructed assets, ranging from infrastructure like roads and hospitals to residential housing, significantly influence our overall quality of life.

However, the industry's impact is not entirely positive. Construction stands as the largest global consumer of raw materials and the built environment is responsible for a substantial portion, 25-40%, of the world's total carbon emissions. This dual nature underscores both the industry's importance and the challenges it poses in terms of sustainability and environmental impact (Bühler et al., 2017). The integration of Industry 4.0 technologies has the potential to assist the construction sector in embracing Circular Economy principles. Examples of these technologies often include pre-manufacturing or off-site manufacturing. By utilizing such technologies, the construction industry can contribute to the realisation of Sustainable Development Goals. This involves optimizing resource usage throughout the entire lifecycle of a project, starting from its initiation and continuing through to its end-of-life phase (de Almeida Barbosa Franco et al., 2022).

Even though new technologies have been proven to enhance productivity in various industries, the construction sector is falling behind. It is not keeping pace with other sectors in terms of utilizing digital tools and is sluggish in embracing advancements in materials, methods, and technology (Barbosa et al., 2017). This leads the construction sector reveal a considerable amount of room for improvement of its performance (Loosemore & Richard, 2015). Various authors have pointed out a diverse set of, organisational, cultural, and institutional obstacles hindering the adoption of technology. (Brandon & Lu, 2008; Loosemore, 2014; Loosemore & Richard, 2015; Sexton et al., 2008; Slaughter, 2000; Widén et al., 2008).

Transitioning from this broader overview of the construction industry, our focus shifts to the specific practices of off-site construction, complex façade systems, and supply chain management.

2.1 Off-site construction

Off-site construction, off-site fabrication, industrialised building, modern methods of construction, prebuilt construction, and prefabricated building are terms used interchangeably. These terms are used in construction, when referring to the process that takes place at a specialised facility where various materials are joined to form a component or part of a larger final assembly on the project site or in other words, on-site (Goulding et al., 2015).

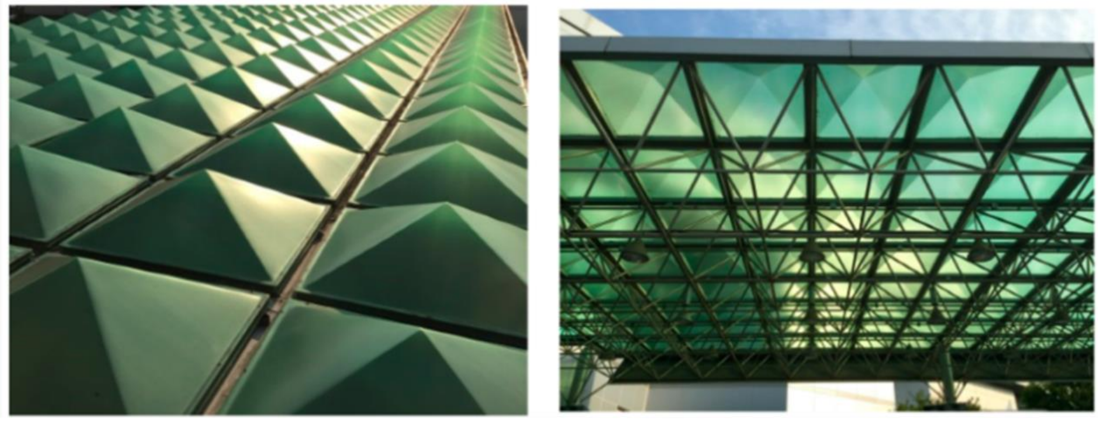
De Almeida Barbosa Franco et al (2022), described this term as an industry 4.0 technology. However, this technology has been around for ages. A historical analysis has documented the global progress of prefabrication, stretching from the 1830s portable colonial cottage to the standardised cast iron castings catalogues of Macfarlane's Saracen Foundry in Glasgow during the 1890s. This evolution showed evidence that showcased the architectural shift from ad hoc building to planned multiple building. The economic importance of off-site fabrication in the aftermath of the Second World War was significant. Prefabrication showed that traditional methods rarely underwent radical alterations and instead exhibited a greater tendency for gradual evolution (Taylor, 2010). Gruneberg (1997) pointed out that since the Second World War, there has been a noticeable rise in the utilisation of prefabricated components in construction. This increase is attributed to the decreasing costs of materials and components in comparison to land and labour. For a long time, literature has identified prefabrication and off-site construction as strategies to enhance the often inefficient and wasteful practices prevalent in the construction industry (Ashworth & Hogg, 2014; Blismas et al., 2006; Fawcett et al., 2005; Gibb & Isack, 2003). McKinsey & Company claimed that the implementation of prefabrication has the potential to be the solution to the low productivity levels observed in the AEC sector over the past two decades (Changali et al., 2015).

The range of off-site construction methods is broad. Many reports have been generated for various sub-sectors, particularly in residential construction. These reports tend to employ distinct terminologies, often exclusive to each other. To maximise the advantages of off-site construction, it is crucial to embrace a manufacturing approach rather than a traditional construction philosophy and process. Applying off-site technologies in an ad hoc manner will only result in limited benefits (Gibb & Isack, 2003). There can be made a distinction between the degree of prefabrication used. This refers to the size and complexity of prefabricated components or configuration of the final product. When there are less prefabricated components, there will be more on-site construction work. There are four main categories of prefabrication: components, panelised structures, modular structures, and hybrid structures (Boafo et al., 2016).

2.1.1 Components structures

Components allow for high customisation and flexibility rate but could result in challenges in tracking and management due to their high quantity. Examples of componentised systems are: stairs, gable ends, wall frames, and roof trusses (Boafo et al., 2016). These components are usually seen as non-structural parts of a building and are not considered complete systems on their own, but they still contribute to the overall structure. Additionally, these components need to be delivered, stored, and skilfully assembled on-site. This assembly process involves a substantial amount of on-site construction before the components are finally put to use (Taylor, 2009). This also means that, under no circumstances, any of these components should be constructed on-site. Components can be seen as the basic level of off-site construction, where there is a minimal percentage of off-site manufacturing (Gibb & Isack, 2003). To provide an illustration of what such components may look like, refer to Figure 2, where (a) depicts the components on the roof, while (b) displays the underlying support structure for the roof.

Figure 2. Roof truss system: roof (a) and the underlying support structure (b).



(a) (b)

Note. Adapted from *Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways by Fred Edmond Boafo, 2016, Sustainability 8 (6), (p. 4)*

2.1.2 Panelised structures

Panelised structures involve flat elements like structural insulated panels and metal frame panels. They are used to construct structural walls, floors, roofs, and columns. These panels enhance the speed and convenience of delivering walls to a site (Boafo et al., 2016). They are manufactured in a factory and then put together on-site to create a three-dimensional structure (Abanda et al., 2017).

Metadecor is using panelised structures for the creation of façades. As panelised construction offers architects significant design flexibility, especially for intricate façade designs, it requires thorough architectural and structural planning before starting the production operations (Hussein et al., 2021). These structures do not contribute to usable space and could include several other sub-assemblies that shapes a part of the building (Ayinla et al., 2019). Various types of panels or panelised assemblies exist, including concrete panels, open panels, closed panels, composite panels, infill panels, structural insulated panels, and curtain walling. Each of these panel types has distinct characteristics, contributing to the dispersion of the typology across different categories (Ross et al., 2006). Figure 3 gives an overview of a curtain wall. (a) shows a picture of a customised curtain wall with transparent glass and integrated PV panels. In (b) the sectional view can be seen of the panel.

Figure 3. Curtain wall: customised curtain wall with transparent glass and integrated PV panels (a) and the sectional view of the panel (b).

(a) (b)

Note. Adapted from *Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways by Fred Edmond Boafo, 2016, Sustainability 8 (6), (p. 4)*

2.1.3 Modular structures

Then there are modular structures, wherein each prefabricated module serves as a volumetric component capable of constituting either an entire or a partial unit which are often 80–95% completed in the factory (Boafo et al., 2016). They are designed for easy assembly, offering a high level of customisation. The construction of the entire building is achieved by assembling various modules. A module is a prefabricated building element that is fully prepared off-site, including all fixtures and fittings (Pan et al., 2008). It is suitable for structures with repeated units such as apartments, schools, offices, dormitories, hotels, and hospitals. Modular construction has many benefits, such as reducing construction time, cost, waste, and environmental impact. However, it also faces some barriers, such as the lack of design guidelines, strong inter-module jointing techniques, and sufficient understanding of the structural behaviour, global stability and structural robustness of modular buildings (Thai et al., 2020).

There are three main construction approaches for stacking modular units: core-based, podium-based, and infilled frame. The core-based approach uses modules that only support vertical loads, while the cores resist lateral loads from wind and earthquake actions. The cores can be made of pre-cast concrete which is a prefabrication technique using components or as an on-site made steel-concrete composite walls (Thai et al., 2020). The podium-based approach uses a platform that supports the modules and allows for mixed use such as open spaces for commercial use or retail or underground car parks. The platform can be designed as a traditional steel, concrete or as a hybrid steel-concrete structure (Thai et al., 2020). The infilled frame approach uses a primary frame that provides stability and fills the gaps with modules. The primary frame can be constructed on-site by conventional methods (Thai et al., 2020). Figure 4 shows the difference of these three types of construction methods for modular high-rise buildings.

Figure 4. Types of construction methods for modular high-rise buildings: Core-based method (a), podium-based method (b), and the infilled frame method (c).

(a) (b) (c)

Note. Adapted from *A review on modular construction for high-rise buildings by Huu-Tai Thai, 2016, Structures 28, (p. 3)*

2.1.4 Hybrid structures

Hybrid structures combine panel and modular systems to construct the entire building (Boafo et al., 2016). Wherein the critical areas of high value, such as kitchens and bathrooms, are usually constructed using volumetric units, sometimes called pods. The remaining structure is built using a framing system, also referred to as semi-volumetric (Gibb & Pendlebury, 2013).

2.2 Complex façade systems

The façade design and construction sector is characterised by its complexity, encompassing a diverse range of materials, varied performance requirements, intricate geometries, and a collaborative, multidisciplinary nature (Voss et al., 2013).

Complex façade systems are getting more commonly employed in the construction of iconic buildings. These systems often incorporate special surfaces to enhance the visual appeal. Traditional on-site construction methods face challenges in achieving the intricate complexities involved. In response, the off-site prefabrication of façade modules emerges as an optimal alternative, allowing for the efficient realisation of these complex designs (Arashpour, 2018). Modern production methods like 3D printing and CNC milling have the potential to enhance the effectiveness of prefabricating building façades, leading to increased efficiency (Xu et al., 2017). CNC milling is applicable for crafting the necessary moulds utilised in the prefabrication of façade modules and panels, including the mechanisms that enable interlocking between the panels (Arashpour et al., 2017). The optimisation of complex façade systems through prefabrication is achieved by embracing the principles of Design for Manufacture and Assembly. This optimisation comes from the incorporation of manufacturing-oriented and advanced processes in the development of the product (Arashpour et al., 2018). Design for Manufacture and Assembly stimulates collaborative efforts across various disciplines during product development, emphasizing the consideration of manufacturing and resource limitations when designing individual components and assemblies (Montali et al., 2017). Additive manufacturing or 3D printing offers the capability to produce prototypes for façade components, including intricate interlocking mechanisms for modules. The utilisation of 3D printing provides advantages over traditional methods, particularly in the production of curved elements for façade modules (Arashpour, 2018).

Façades are highly customised industrial products because the level of involvement of the customer is high. A façade therefore uses "flexible industrial prefabrication" (Eekhout, 2008). Façades fall into the engineer-to-order category with their high customisation degree, as each client request initiates the delivery process from the design stage. While this approach results in unique products, it introduces additional time and risk to the overall façade delivery. The level of customisation in façades varies, ranging from one-of-a-kind traditionally crafted products and customised solutions within predefined systems to the selection of standard systems (Montali et al., 2017). Metadecor employs the approach of customised solutions within predefined systems, allowing clients the flexibility to select from predetermined options that can be further customised to meet their specific preferences.

Reducing customisation, such as through standard system types, may streamline the design process and expedite delivery but must be balanced with the need for a diverse range of possibilities to meet architectural requirements (Montali et al., 2017). Occasionally, when working on the design of a complex system featuring interrelated constraints, designers may lack awareness of all the relationships among the variables. Consequently, they might overlook the impact of alterations in one part of the design on others. Therefore, it proves beneficial to assess the sensitivities of all variables during the conceptual phase (Chandrasegaran et al., 2013).

The design of a façade is a complex and collaborative interdisciplinary activity, with the main contractor or façade consultant playing a pivotal role in coordinating design solutions among subcontractors, the engineering design team, architects, cost consultants, and clients. The design process follows a typical conceptual/developed/detailed workflow, evolving from defining basic geometric features and broad performance criteria to providing detailed information for production and installation. The focus shifts from the overall building context, establishing generic features like the he window-to-wall ratio which shows the extent to which a building's façade is comprised of windows rather than solid walls, to more detailed analyses, such as 2D/3D element analyses for specific performance assessments (Montali et al., 2017).

Iterative checks are conducted at each stage to ensure adherence to design requirements, evaluating aspects like manufacturability, cost, expected performance, and alignment with the architect's design intent. The process generally advances without back cycling, except for unforeseen errors or manufacturing constraints (Montali et al., 2017).

2.3 Supply chain management

For over 20 years, The business landscape has witnessed a significant shift towards adopting supply chain management as a fundamental business strategy, driven by changes in manufacturing environments, including the rise of evolving customer demands, information technology, and globalisation (Vonderembse et al., 2006). Logistics and materials management, as indicated by Christopher (2022), have historically been the origins of all supply chain concepts. The field of supply chain management has shifted its attention towards comprehending the fundamental relationships within supply chains, moving beyond the conventional buyer-supplier partnerships. This has resulted in research with a broader scope and gave greater insights in how projects function (Almadhoob, 2020). Over time, there has been a progress towards broader approaches in the supply chain. This resulted in marketing and supplier involvement in product development also becoming part of the supply chain (Vrijhoef, 2011). In this study the definitions for supply chain and supply chain management are defined according to Handfield and Nichols. Where: *"The supply chain encompasses all activities associated with the flow and transformation of goods from the raw materials stage (extraction), through to the end user, as well as the associated information flow both up and down the supply chain"* (Handfield & Nichols, 1999). And *"Supply Chain Management (SCM) is the integration of these activities through improved supply chain relationships, to achieve a sustainable competitive advantage"* (Handfield & Nichols, 1999).

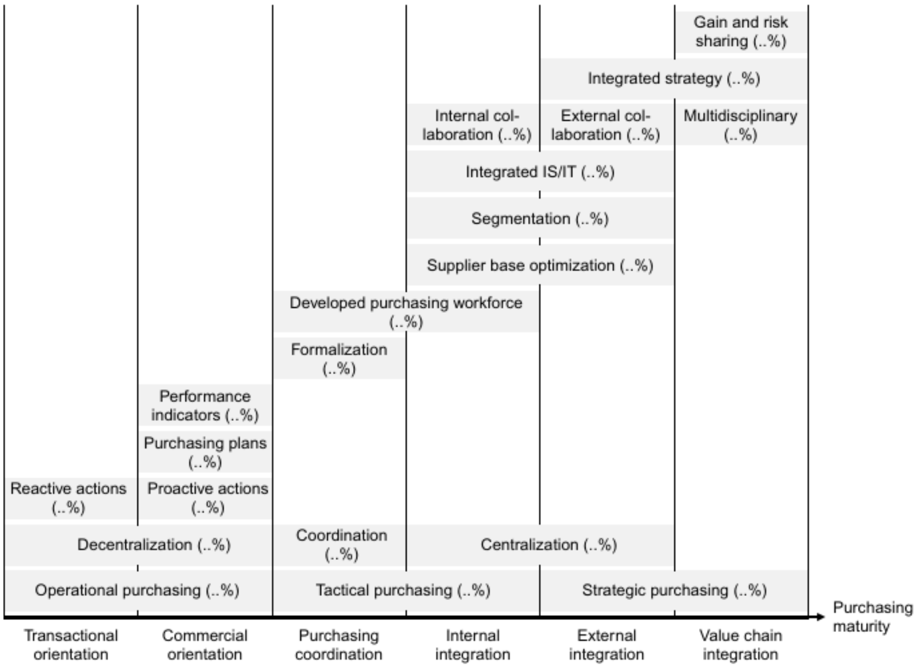
Multiple studies have been conducted on the development of organisations towards achieving effective supply chain management (Koivisto, 2013). Schiele indicated that: “A Maturity model describes several-auditable-stages an organisation is expected to go through in its quest for greater sophistication” (Schiele, 2007). The first maturity model to exist was that described in Reck and Long (1988) called “Strategic stages in the development of a purchasing function” (Axelsson et al., 2005; Rozemeijer, 2000; Schiele, 2007; Van Weele et al., 1998). Later Van Weele came up with a purchasing development model which took account of multiple previous development models which added to the completeness of the overall theory, the evolutionary stage model as described by Keough (1993) was the basis for this model (Van Weele et al., 1998). The model of Van Weele takes into account different previous maturity models, and is also tested in the construction industry (Bemelmans et al., 2013).

The purchasing development model of Van Weele consists out of 6 stages. Which shows the development of purchasing inside an organisation from stage 1 to stage 6.

- Stage 1, ‘Transaction orientation; Serve the factory’ can be seen as the initial phase, where purchasing primarily focuses on ensuring a steady supply of materials and components for production. There is no formal strategy in place, and goals are basic and intuitive. The culture is reactive, and management evaluates success based on the absence of complaints. Information systems, if present, are rudimentary and administratively oriented.
- Stage 2 is named ‘Commercial orientation; lowest unit price’ where the focus lays on negotiating lower prices with suppliers. This stage emphasises cost reduction and autonomy for buyers. Specialist buyers are employed to negotiate favourable deals, and performance is measured primarily by cost savings. The culture fosters tough negotiation tactics, and management closely monitors price variance and supplier delivery performance.
- In stage 3, ‘Co-ordinated Purchasing’, the strategy is more coordinated with centralised departments implementing uniform buying policies. Emphasis is placed on cross-unit coordination and compliance with national contracts. Although some strategy formulation occurs, the broader organisation may still undervalue the role of purchasing. Supplier management becomes crucial, focusing on synergy and differentiated supplier strategies. Formalisation of processes accelerates, and communication improves, although information systems remain somewhat disjointed.
- Stage 4, ‘Internal integration cross-functional purchasing’. In this stage, the internal integration becomes more important, with a focus on cross-functional problem-solving to reduce total systems costs. Purchasing becomes more process-oriented, aligning with the internal customer needs. Attention to non-production purchasing increases, and purchasing's strategic importance gains recognition. Team-based management and integration efforts dominate, although information systems integration with suppliers remains incomplete.
- Stage 5, ‘External integration; supply-chain management'. Here, the external integration marks a shift towards supply chain management, with a pronounced outsourcing strategy and collaboration with supply partners. Purchasing emphasises the impact of the supply chain on company resources and actively supports non-production buying. Integration with suppliers and cross-functional teams intensifies, facilitating integrated supply chain management. The culture encourages participation and consensus decision making, with a focus on total cost of ownership principles and strategic supply chain management. Information systems in this stage are also integrated with those of partner suppliers.
- Preliminary Stage 6, ‘Value chain orientation’. In this stage, purchasing aligns its strategy with delivering value to end-customers, integrating with marketing functions and suppliers to optimise the value chain. The culture becomes entrepreneurial, driven by a shared vision of customer satisfaction. Information systems are fully integrated internally and with partner suppliers, enabling seamless coordination across the value chain (Van Weele et al., 1998).

Bemelmans et al. (2013) presents a tool for an effective assessment of purchasing maturity in construction organisations based on the purchasing model described in Van Weele et al. (1998). Where a company could gain quick insights into its current level of maturity based on 20 characteristics. This quick scan could give insights into possibilities for improving the performance (Bemelmans et al., 2013). Figure 5 shows the 20 characteristics evident at every stage of the development model seen in Van Weele et al. (1998). Detailed descriptions of these characteristics can be found in Appendix 1.

Figure 5. Graphical depiction of the developed concise purchasing maturity tool.



Note. Reprinted from *Designing a tool for an effective assessment of purchasing maturity in construction by Jeroen Bemelmans, Hans Voordijk and Bart Vos, 2011, Benchmarking: An International Journal, (p. 350)*

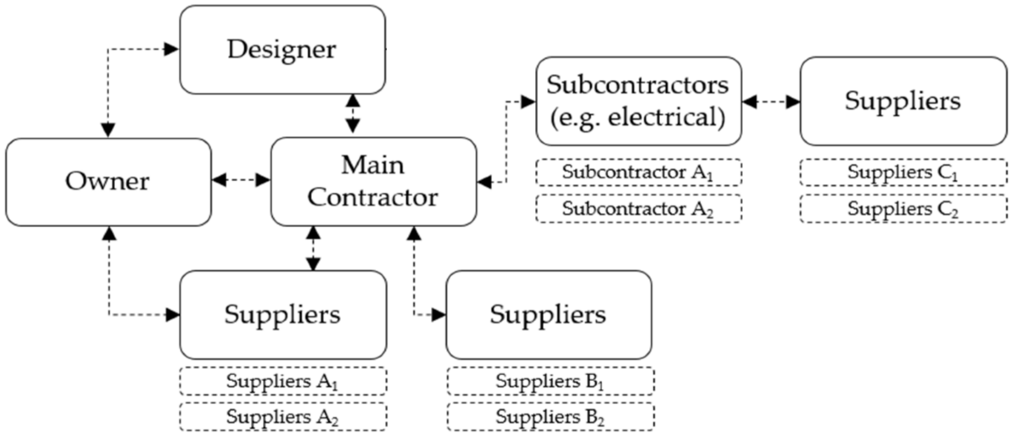
2.3.1 Construction supply chain management

When it comes to the methods and practices related to procurement and supply-chain management, the construction industry is one of the least advanced sectors (Barbosa et al., 2017). The construction supply chain has distinct characteristics in both structure and function. Firstly, it operates as a converging supply chain, transporting all materials to the construction site for the assembly of a specific object. In contrast to manufacturing systems handling multiple products, the construction supply chain centres around a singular product, resembling a "construction factory." Secondly, the construction supply chain is inherently temporary, primarily tailored for one-off construction projects. This entails repeated reconfigurations of project organisations, resulting in an environment characterised by instability, fragmentation, and a noticeable divide between the design and construction phases (Vrijhoef, 2000). This uniqueness makes the supply chain of a construction project distinct, tailored exclusively to meet the needs of that particular project. (Shishodia et al., 2019). Lastly, the construction supply chain follows a make-to-order model, which requires the creation of a new product or prototype for each project. While certain projects may share similarities in processes, the overall approach is marked by limited repetition, with each project presenting a unique set of requirements (Vrijhoef, 2000).

Material flows in traditional construction meet on on-site production, but unlike large manufacturing companies, job sites lack the power to coordinate the supply chain efficiently. Demand from job sites is unstable, and in cases of changes, the limited flow of information to suppliers and subcontractors hampers efficient coordination, resulting in waste. Subcontractor involvement in multiple projects simultaneously adds complexity, making subcontractor resource availability a critical factor. Some subcontractors coordinate material flows with their suppliers, impacting the risk of material delays on job sites (Vrijhoef, 2000).

An overview of a typical construction supply chain can be seen in Figure 6. A typical construction supply chain is often viewed as an extensive and intricate network involving numerous organisations, such as clients/owners, designers, general contractors, subcontractors, and suppliers. These entities are interconnected through the exchange of information, materials, services, products, and financial transactions (Studer & De Brito Mello, 2021).

Figure 6. A typical construction supply chain.



Note. Adapted from *Core Elements Underlying Supply Chain Management in the Construction Industry: A Systematic Literature Review by Walter Puppo Struder, 2021, Buildings 11(12), (p. 2)*

Supplier performance is influenced by numerous factors, with risks associated with long lead time products and limited capacity being noteworthy. Suppliers prioritise orders either for preferred customers or to enhance internal efficiency. Therefore, construction managers should come up with strategies to minimise risks related to the procurement of materials from such suppliers (Azambuja & O'Brien, 2008).

Vrijhoef et al. (2011), mentioned that theoretical topics across four distinct domains exist through the supply chain: human resource management and social topics; technological and production topics; organisational topics; and procurement and economical topics.

- Looking at it socially, supply chain management involves coordinating the efforts of individuals collaborating on a task that is broken down into specialised activities. This coordination is achieved through communication. Subsequently, this communication should result in commitment to ensure the successful completion of the jointly coordinated activities.
- Looking at it from a production standpoint, the emphasis is on minimizing or eliminating any kind of waste, specifically activities that don't contribute value, present in the production systems of the organisations involved in the supply chain.
- The organisational domain goes into the supply chain and its individual entities, the distribution of business activities raises a governance challenge. This challenge involves determining how to consolidate and align the capabilities of individual organisations within the supply chain.
- Viewed through an economic lens, the objective of supply chain management is to minimise production costs and, more specifically, transaction costs. This involves seeking cost reductions and ensuring alignment in coordination and communication within the supply chain. Instead of dealing with each transaction in isolation, advantages come from organizing groups or clusters of interconnected transactions within the broader framework of the supply chain.

2.3.2 Off-site construction supply chain

Effectively managing the supply chain in off-site construction is a critical challenge for ensuring the successful completion of off-site construction projects (Wang et al., 2015). The extended scope of the off-site construction supply chain means it oversees the entire process, including manufacturing, transportation, delivery, and the installation of prefabricated products. This results in more complexity, involving multiple processes and stakeholders, in contrast to traditional construction supply chains (Wang et al., 2017).

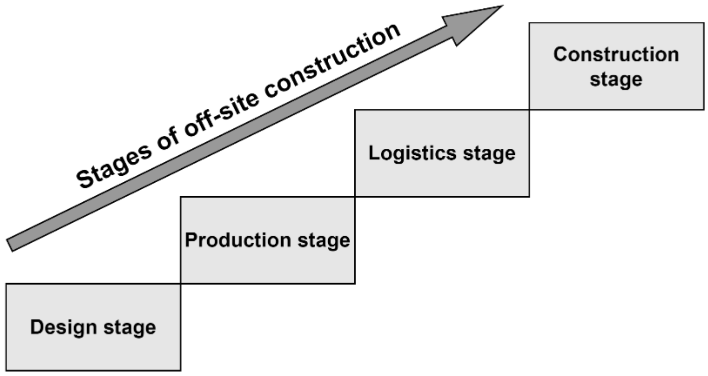
The supply chain in off-site construction is typically longer compared to traditional construction. This is because there are more production steps involved and multiple locations where production occurs. This extended chain is a result of building components being manufactured off-site and later transported to the construction site for assembly. This results in a greater total variability. Thus, high requirements for the cooperation and coordination in the design, planning and installation of the structures are required. Besides this, a greater amount of design work is required, and it must be completed earlier than on-site construction, mainly due to prefabrication lead times. This contrasts with the often-delayed determination of stable design solutions in traditional construction, leading to incomplete and changing orders. The time to discover an error of the components takes also longer than on site construction, and the precision of construction is higher than on-site construction where dimensional variation between components can be compensated (Koskela, 2003). Moreover, stakeholders from various companies often prioritise their individual goals and values, showing limited regard for the overall efficiency of the supply chain. This tendency becomes especially pronounced when a company operates on a project-by-project basis (Luo et al., 2020).

The off-site construction supply chain is filled with risks spread across its various stages, encompassing design, production, logistics, and on-site assembly (Wang et al., 2017). Any disruption occurring at the initial stages of the off-site construction supply chain has a cascading effect, negatively impacting subsequent stages and leading to an overall inefficient supply chain. Effective supply chain management is required to fully leverage the advantages of off-site construction and optimise project benefits (Han et al., 2022). So, in off-site construction a different approach to supply chain management is taken, where coordinating different aspects of the project at the same time are required rather than step by step methods as done in regular construction (Smith, 2016).

The off-site construction supply chain is a system that begins with the detailed design and creation of drawings for the structure's components, to be later manufactured in a facility. These components are then stored and transported to construction sites for installation, with customisation to fit the specifications of each project. Due to the customised nature of these components, prefabricators wait until receiving orders to produce them. Additionally, the heavyweight and bulkiness of these components prevent contractors from maintaining large buffer stocks to offset potential delivery delays. A disturbance at the beginning of the off-site construction supply chain has a domino effect on the following stages, leading to an overall inefficiency in the supply chain (Hsu et al., 2018).

For prefabricated components construction, panelised construction, and for modular construction there can be made a distinction between four supply chain stages. In off-site construction the architects should understand that the construction is more inclined towards the manufacturing side rather than the construction side to achieve a successful project. The first stage is the design stage where the design of the building and planning should be made. This requires the application of integrated design processes. This stage will be followed by the production stage where the components will be manufactured at an off-site facility. Subsequently, the logistics stage will begin. In this stage the smooth transport of components is required with a planned logistics management to ensure an optimal schedule for the on-site construction stage. In the last stage, the on-site construction stage, the assembly of the components will be done, to eventually finalise the building (Hussein et al., 2021; Khan et al., 2023). Figure 7 shows this process simplified.

Figure 7. Stages of off-site construction.



Note. Own work

2.3.3 The customer order decoupling point

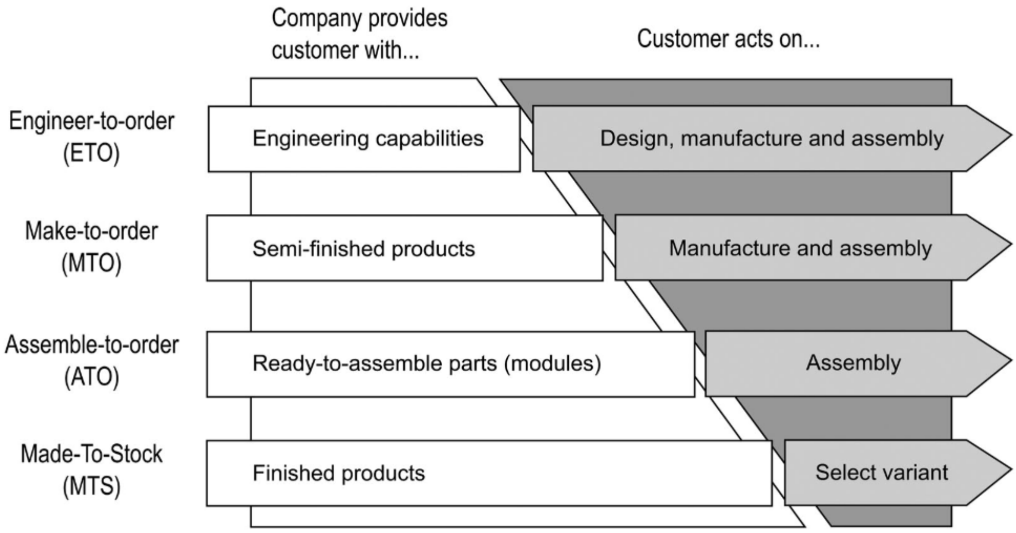
The construction industry involves a complex network of participants, including owners, designers, general contractors, subcontractors, and various suppliers offering different technologies at different project stages. These entities collaborate to create a unique supply chain configuration. This encompasses the on-site and off-site production (Azambuja & O'Brien, 2008). Even for small projects which involve multiple subcontractors, each with its own supply structure, the scale of a construction supply chain becomes extensive. Thus, construction projects are viewed as composed of multiple supply chains, each exhibiting specific behaviours influenced by the type of product delivered to the project site (Azambuja & O'Brien, 2008).

The customer order decoupling point (CODP) is a way to distinguish between decisions and activities occurring prior to and following the receipt of a customer order. Four general types of supply chains structures exist: engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and Make-to-Stock (MTS). Each type has distinct characteristics, lead times, and manufacturing complexities (Arbulu et al., 2005; Haglund et al., 2023).

ETO products are custom-made based on detailed customer specifications, often involving long lead times and complex engineering processes. MTO products are manufactured once customer orders are received, with lead times varying based on manufacturing complexity. ATO products are assembled after customer orders, typically using standard components, and have shorter lead times. MTS products are commodities with short lead times, such as consumables. MTS manufacturers maintain inventory, but distributing these products can be complex (Arbulu et al., 2005; Haglund et al., 2023). The location of the CODP varies among the four supply chain structures. For an ETO product, the customer acts on the design and subsequent stages. For the MTO the location of the CODP is at the manufacturing and assembly stage. At the ATO the decoupling point takes place at the assembly stage, and for the MTS it is from the finished stock (Haglund et al., 2023; Montali et al., 2017). This leads to a company fulfilling specific customer requirements. In the case of ETO products, the focus is on providing engineering capabilities. MTO products involve delivering semi-finished goods, ATO relates to ready to assemble parts, and MTS encompasses delivering finished products directly to the customer (Montali et al., 2017).

The representation of an ETO product model requires incorporation of diverse processes carried out by different entities like designers, suppliers, general contractors and engineering firms. Modelling supply chain processes for ETO products needs a consideration of multiple information flows, as these directly impact both the manufacturing process and the delivery of the product. In contrast, modelling an MTS product involves fewer entities, typically the general contractor or subcontractor and the supplier. Information flow is generally confined to the transaction process, though modelling may still need to encompass processes directly or indirectly linked to material flows (Azambuja & O'Brien, 2008). The different levels of customer influence on the supply chain can be seen in Figure 8.

Figure 8. The customer order decoupling point.



Note. Reprinted from *Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends by Jacopo Montali, 2017, Architectural Engineering and Design Management 14, (p. 79)*

Both the MTO and ETO strategies are characterised by product specifications, different levels of customisation, variable demand, long flow times, lead times and process duration. But there are differences between the strategies. In MTO, there already is an existing design of the product at the time of when an order is placed, although there can be made some modifications, only the manufacturing and assembly of the product are done once the order has been confirmed. In an ETO strategy on the other hand the design, manufacturing and assembly are done once the order has been confirmed (Hendry, 2010). In both strategies, low-volume production is standard, with multiple projects being executed simultaneously, and being on time is the most important Key Performance Indicator (KPI). This is because penalty costs are dependent on lateness, and early deliveries may also prove inconvenient (Barbosa & Azevedo, 2018).

With ETO products the specification of the product are uncertain, because the customers require the design of a completely new product (Akinc & Meredith, 2015). The engineering process is therefore considered as the bottleneck, and the core process which is never outsourced. In an ETO environment, uncertainty and variability exist due to the presence of different projects at various completion levels, which may also undergo changes at any time (Barbosa & Azevedo, 2018).

2.3.4 Project complexity

Metadecor is a project-based organisation. In the Project Management Institute's guide, a project is defined as “a temporary endeavour undertaken once to create a unique product, service, or result” project management is “the application of knowledge, skills, tools, and techniques to meet project requirements” (PMI, 2008). A distinction is made between process activities comprising unique, discrete, non-routine project tasks, and those characterised by standardised, ongoing, and repetitive activities. It has long been recognised that projects contain repetitive elements (PMI, 2008). So conventionally, project management textbooks and authoritative organisations have operated under the assumption that projects are uniform and can be handled through a standardised, one-size-fits-all approach, employing standardised procedures and organisational structures (Roehrich et al., 2024).

More recently, it has been emphasised that this repetition does not diminish the fundamental uniqueness of project work (PMI, 2008). Given that projects face uncertainty, complexity, and environmental dynamics, it is crucial to maintain adaptability in plans and adjust projects during execution to handle unforeseen circumstances as they arise (Roehrich et al., 2024). While the outcome of each project is distinctive, the activities involved vary from unique to repetitive (Lundin & Söderholm, 1995). Innovative, nonrecurring, and highly uncertain tasks such as developing a new product or complex system are seen as an unique project, whereas standardised, routine, and predictable tasks that will be repeated in the future are seen as a repetitive project (Davies & Brady, 2000). An organisation may engage in a range of unique and repetitive projects, including hybrid projects that combine both unique and repetitive tasks (Roehrich et al., 2024).

Construction projects are becoming intricate, and this complexity is on the rise, primarily due to the fragmented nature of the industry. There are many diverse entities operating in a construction project like architects, engineers, consultants, and contractors which are all operating for a finite duration. The industry also has a high capacity to generate and accumulate vast amounts of data. The complexity within a project organisation is influenced by factors such as project size and uncertainty, which tend to escalate as the number and diversity of contributing entities increase. With the increasing concerns regarding buildings' environmental impact, the requirements for the buildings have become more strict (Pantazis & Gerber, 2019). Besides this, detailing is increasingly a collaborative process involving multiple sectors. Both the concern for environmental impact and the intricate detailing necessitate designers from different industries to collaborate in contemporary architecture (Gawell & Grabowiecki, 2021).

When projects involve multiple organisations collaborating to coordinate the production of the end product in uncertain and dynamic environments, they are viewed as interorganisational (Jones & Lichtenstein, 2008; Sydow & Braun, 2018). Research on these types of projects has been categorised under various names, including major projects, interorganisational projects, systems of systems, megaprojects exceeding 1 billion dollars, large engineering projects, and global projects (Roehrich et al., 2024). According to Shenhar (2001) there exist three types of projects based on their increasing degree of complexity: assembly, system, and array. The assembly project is regarded as the most simple project, which could be a single component, subsystem or a product or service. This type is most of the time done in-house by a small development team. A system project is seen as more complex because it has many interacting components and subsystems, arranged in a platform with multiple functions that together meet a user or operational requirement. Then there are array projects, these projects are the most complex with a large collection of systems, each providing a specific function at work together to accomplish a goal. An interorganisational project often takes the form of a system or array project. These projects are typically overseen as part of a comprehensive interorganisational program consisting of interconnected projects, aimed at achieving strategic objectives that exceed the capabilities of individual projects alone (Roehrich et al., 2024).

2.3.5 Comparative analysis of ETO supply chains

The design process of a complex façade is a highly interdisciplinary and interdependent activity. This design process is similar to the shipbuilding design process. There are the same strict delivery times, they both produce ETO products, with low production batches. Besides this, the shipbuilding sector is just as the AEC sector operating in a fluctuating market (Montali et al., 2017).

As said earlier modular volumetric construction leans more towards the make to order strategy because of the more standardised practices (Robinson et al., 2011). An ETO approach requires the development of engineering solutions before product fabrication, while the MTO production is based on already existing configurations. ETO solutions can be classified as "light" if they involve minor customisations or as "heavy" when the final solution requires significant engineering with a high level of customisation.

These applications are necessary when customer requirements cannot be fulfilled through a catalogue of pre-configured solutions (Cicconi et al., 2020). According to Sharma et al. (2012), the production of a ship is more of a construction process or assembly rather than a production process. Both a ship and a building structure are designed on the basis of the specification of the customer, before being built in the case for a building structure or manufactured in the case of a ship. Both products are composed of different components that are used in order to be able to justify the different usages in the two industries (Boton et al., 2018). In the shipbuilding sector the services and equipment on the shipyard create around 70% of the value of the end product, this combined with a large number of components from the supply chain makes internal and external collaboration of companies a critical factor for the design of a ship (Montali et al., 2017).

Although the shipbuilding industry can be compared to the creation of complex façade systems, they do not use the same terminology, ontologies or taxonomies. For example in the construction industry the technology used to facilitate collaboration and optimisation of information flows throughout the project lifecycle is called Building Information Modeling (BIM), this is similar to Product Lifecycle Management in the manufacturing industry which is a strategy for creating and sustaining a product-centric knowledge environment, encompassing design tools, data warehouse systems, product maintenance. It enables just as with BIM, collaboration among the stakeholders throughout the products lifecycle. Although there are differences between these industries, they could benefit from sharing their best practices with each other (Boton et al., 2018).

Research on supply chain management within specific product development processes revealed additional similarities between ETO companies in the construction and shipbuilding sectors. Through the analysis of various cases, it was found that customisation tends to foster supply chain integration, characterised by collaborative relationships and information sharing throughout the supply chain. The customisation increases product complexity, thereby necessitating greater engagement from both customers and suppliers. This dynamic is particularly evident in the shipbuilding sector (Pero et al., 2015).

Pero et al. (2015) confirmed that ETO products could be identified of three main categories of product and their supply chain.

1. Modular products with loosely coupled supply chains
2. Pre-assembled products with modular supply chains
3. Traditional (non-modular) products with integrated supply chains

The study confirmed with this the proposition that when product modularity increases, the supply chain integration diminishes (Pero et al., 2015). With an integrated supply chain, all players are directly engaged and work closely with each other from the design phase until the building phase (Fine, 2000). Modular supply chains consist of relatively flexible and interchangeable relationships among suppliers, customers and partners (Doran & Giannakis, 2011). In such a supply chain there is a tight integration among the players of each group but a low integration between the groups (Droge et al., 2004). In a loosely coupled supply chain, the actors inside the supply chain have very limited interactions and suppliers. These suppliers are often geographically dispersed and typically have minimal involvement in the design phase, nor do they engage in regular interactions. Main contractors occasionally purchase off-the-shelf materials from a catalogue (Voordijk et al., 2006).

2.4 Conclusion of theory

In summary, there are three primary types of off-site construction, including components structures, panelised structures, modular structures, and there exists a mix between those called hybrid structures (Boafo et al., 2016). There has been a growing utilisation of complex façade systems in the construction of iconic buildings with special surfaces to enhance the visual appeal (Arashpour, 2018). For these prefabricated structures the level of customisation varies, ranging from ETO customised solutions to standardised systems, each with its implications for design complexity, delivery time, and supply chain management (Arbulu et al., 2005; Haglund et al., 2023).

Over the past two decades, there has been a notable shift towards adopting supply chain management as a core business strategy (Vonderembse et al., 2006). In the context of construction, supply chain management faces unique challenges due to the industry's distinctive characteristics. Unlike traditional manufacturing systems that handle multiple products, the construction supply chain revolves around singular projects, resembling a "construction factory" (Vrijhoef, 2000). Numerous studies have investigated how organisations develop to achieve effective supply chain management (Koivisto, 2013). The development model described in Van Weele et al. (1998) is one of the most comprehensive maturity models, incorporating various previous maturity models (Bemelmans et al., 2013). The off-site construction supply chain is marked by increased complexity, variability, and risks compared to traditional construction, requiring careful coordination and management across design, production, logistics, and on-site assembly stages (Wang et al., 2017). Each supply chain type exhibits unique characteristics, lead times, and complexities. ETO products are custom-made based on detailed customer specifications, involving long lead times and complex engineering processes. While MTS products, such as consumables, are commodities with short lead times and are often kept in inventory (Arbulu et al., 2005; Haglund et al., 2023). Research has demonstrated that supply chain management has several similarities between the construction and shipbuilding sectors (Pero et al., 2015), particularly within the complex façade industry and the shipbuilding sector (Montali et al., 2017).

It has been noted that when a project involves collaboration among multiple organisations to coordinate the production of the end product in uncertain and dynamic environments, it is considered interorganisational (Jones & Lichtenstein, 2008; Sydow & Braun, 2018). In a project, the outcome is always distinctive, yet the activities range from unique to repetitive. Consequently, an organisation could be involved in a variety of both unique and repetitive projects (Roehrich et al., 2024). Thus, understanding the complexities and dynamics of the off-site construction supply chain is crucial for effectively managing and executing projects in this ever-evolving industry.

3 Methodology

The methodology utilised two fundamental theories: the theory underlying Critical Success Factors (CSFs) and the Analytical Hierarchy Process (AHP). These theories will be thoroughly examined in chapters 3.1 and 3.2, respectively, providing detailed insights into their principles and applications. Chapter 3.3 will go into the five research phases of the project as depicted in Figure 1.

3.1 Critical Success Factors

A vast amount of literature is available about the success factors for successful supply chain management in off-site construction (Wuni & Shen, 2023). This is also the case for a resilient supply chain in off-site construction, which is described as an emergent research domain (Liu & Liu, 2023). However, specifically for the panelised construction, success factors do not exist. The CSFs approach was first developed by Rockhart (1979) and defined as *"The limited number of areas in which satisfactory results will ensure successful competitive performance for the individual, department, or organisation. CSFs are the few key areas where 'things must go right' for the business to flourish and for the managers goal to be attained."*

Several benefits of using the CSFs approach include the focusing of management attention on the critical areas of business, and an understanding of the priority areas of a business. The method is also easy to understand, relevant, and helpful for managers, this makes them more committed and involved in CSF research. The method can also be modified in various ways to meet the needs of individual studies (Boynton & Zmud, 1984; Henderson et al., 1987; Peffers et al., 2003; Premkumar & King, 1994; Rockart, 1979).

1. The development of CSF method techniques has seen various adjustments and expansions. Researchers modified the techniques for identifying CSFs, by compiling lists from literature and validating them through participant questionnaires (Jennex & Adelakun, 2003; Sabherwal & Kirs, 1994). Also, like substituting or combining CSF interviews with written questionnaires (Martin, 1982; Somers & Nelson, 2001). These adaptations aim to maximise insights gained from CSF studies (Cooper, 2009).
2. Secondly, a notable adaptation by Bullen and Rockart (1981) involved broadening CSF study participants to include individuals from various organisational hierarchy levels, moving beyond the focus on executive and senior management (Bullen & Rockart, 1981). Researchers argue that involving participants at different levels provides diverse perspectives on CSFs (Bergeron & Bégin, 1989; Boynton & Zmud, 1984), creating a detailed representation of how different individuals within the organisation perceive and prioritise CSFs (Bergeron & Bégin, 1989; Shank et al., 1985).
3. Third, while originally concentrated on determining CSFs at a strategic level for organisations, the CSF method has been applied to define CSFs within specific business processes, projects, and strategies (Cooper, 2009). For example, Somers and Nelson (2001) analysed the impact of twenty-two CSFs throughout the Enterprise Resource Planning system implementation process, dividing it into five stages. This approach enriches the understanding of CSFs within the context of each implementation stage.
4. Lastly, the outcomes of CSF studies typically yield lists of four to eight CSFs (Rockart, 1979), but some studies report more (Jennex & Adelakun, 2003; Somers & Nelson, 2001; Wuni et al., 2020). While criticised for generating lengthy lists, researchers have presented CSFs in various formats, including categorisation schemes (Jennex & Adelakun, 2003; Zhao, 2021). Zahedi (1987) proposed a CSF hierarchy, and there were also attempts to prioritise CSFs, showcasing the method's adaptability and flexibility in research (Somers & Nelson, 2001; Wuni et al., 2020).

The success determinants for off-site construction in general range from factors such as design for supply chain management and improved interfaces between off-site and on-site work packages to effective communication and information sharing and early involvement of critical supply chain stakeholders (Wuni & Shen, 2023). Another study by Cano et al. (2015) identified similar findings.

3.2 Analytical Hierarchy Process

The research employed the Analytic Hierarchy Process (AHP) as the method for prioritising success factors in Metadecor's off-site construction supply chain. AHP is a multi-criteria decision making technique that allows for the systematic comparison and ranking of factors based on their relative importance (Saaty, 2004). AHP stands out among methodologies used in similar studies due to several advantages. AHP aids respondents by guiding their focus toward pairwise factors comparisons instead of requiring consideration of numerous factors simultaneously (Inayat et al., 2015). It also allows for some level of inconsistency in expert judgements during analysis (Gudienė et al., 2014). Lastly, when dealing with subjective factors in decision making, AHP proves to be more effective compared to other tools, providing a means to address subjectivity in respondents, as highlighted by Kog and Loh (2012).

AHP involves four main steps:

- Problem Definition: The first step is to define the problem and identify the required knowledge.
- Decision Problem Structuring: The second step requires structuring the decision problem using a three-level hierarchy. The top level signifies the goal, followed by a second level with sub-

criteria, and the third level containing the criteria. This hierarchical organisation aids in handling complexity by arranging factors from the general to the specific.

- Pairwise Comparisons: Following the structuring process, matrices for pairwise comparisons have to be created. Elements in upper levels are utilised to compare and assess elements in the level directly below.
- Weight Assignment: Using priorities derived from the comparisons, weights are assigned to priorities in the level immediately below. This process is repeated for each element within that level. Weighted values for each element in the lower level are aggregated to determine its overall or global priority. This weighing and combining process is done until the final priorities in the bottommost level are established (Saaty, 2008; Saaty & Vargas, 2012).

3.3 Research phases

To address the central research question, the study is structured into five distinct phases. This section will explore each of these phases in detail, offering an in-depth discussion of each phase.

3.3.1 Success factors identification

Based on existing literature, a preliminary list of potential CSFs for effective supply chain management in the construction sector was compiled. According to Wuni et al. (2023) there already is a considerable documentation of CSFs in off-site construction. This existing literature formed the basis for the list of success factors for the supply chain management in panelised construction. This way of identifying CSFs is a similar approach to methods used by Wuni et al. (2023) and Zhao (2021). This literature review was conducted using the Scopus database, due to its wider coverage of scientific publications compared to other databases (Darko et al., 2020). Utilizing a single database enhances the reproducibility of the search process, a practice widely employed in prior Construction Engineering and Management reviews (Wuni, Shen, & Osei-Kyei, 2019). To identify articles relevant to the study's objectives, we employed commonly used keywords, phrases, and individual words in our search. For investigating CSFs, we utilised phrases such as 'critical success factors', 'success factors', 'key success factors', 'determinants', 'factors', 'influence factors', and 'requirement'. To focus solely on articles related to supply chain management, there have been used phrases like 'supply chain' and 'supply chain management'. Additionally, to narrow down the search scope to prefabricated construction, there are employed synonyms and related terms such as 'prefabricated construction', 'panelized construction', 'panelised construction', 'modular construction', 'MIC', 'Modular integrated construction', 'Prework', 'offsite construction', 'off-site construction', 'offsite fabrication', 'industrialized building', 'modern methods of construction', 'prebuilt construction', and 'prefabricated building'.

The following search string was used to gather relevant articles: TITLE-ABS-KEY ("prefabricated construction" OR "panelized construction" OR "panelised construction" OR "modular construction" OR "MIC" OR "Modular integrated construction" OR "Prework" OR "offsite construction" OR “off-site construction” OR "offsite fabrication" OR "industrialized building" OR "modern methods of construction" OR "prebuilt construction" OR "prefabricated building" AND "supply chain" OR "supply chain management" AND "critical success factors" OR "success factors" OR "Key success factors" OR "determinants" OR "factors" OR "influence factors" OR "requirement") AND (LIMIT-TO (LANGUAGE , "English")).

These keywords have been chosen based on related previous studies (Arshad & Zayed, 2022; Liu et al., 2020; Lu et al., 2022; Wuni & Shen, 2023; Zhao, 2021). In this study only English language articles were considered. The full articles were read to assess the substantive relevance, and there was no time limit or limit on publication type adopted. Besides this, snowball sampling was used to identify additional relevant articles. Each relevant initial study was employed to initiate backward snowballing. In backward snowballing, the researcher explores relevant studies listed in the references of each study from the initial set (Hussein & Zayed, 2021). The decision has been made to exclusively incorporate CSFs that have been cited at least twice in prior studies, aiming to establish a robust and well-founded groundwork for the research. This strategic choice not only ensures the credibility of the selected factors but also serves to maintain a concise set of CSFs. This deliberate limitation enhances the practical applicability of the factors, aligning with the concept that CSFs represent a select set of elements where favourable outcomes guarantee successful competitive performance (Rockart, 1979). This approach has been employed in earlier similar research (Antwi-Afari et al., 2018; Robert & Chan, 2015; Wuni et al., 2022). The identified relevant articles should constitute CSFs or requirements for a successful or a resilient supply chain in off-site construction.

3.3.2 Expert-led success factors selection

Subsequently, a panel of experts were involved in the AHP process. Their expertise resulted in selecting the success factors which were obtained from the literature. Nine experts within the supply chain of Metadecor evaluated the relevance of the identified success factors. This methodology, as employed in prior research of a similar nature, involves favouring the dominant perspective in cases of divergent opinions by utilizing an odd number of participants (Wuni et al., 2020). Because it was unclear whether or not the list of CSFs is complete, the experts both within and outside of Metadecor were consulted to determine if there were any additional factors within Metadecor's supply chain. In this way factors critical to Metadecor and factors critical to the whole supply chain regarding Metadecor were identified. From each of the four supply chain stages—design, production, logistics, and assembly—one expert from Metadecor and one external expert were included in the panel. Thus, two experts from each phase were responsible for assessing the relevance of the factors and proposing additional ones as needed. This panel of experts consists out of a mix between employees from various positions like a supplier, main contractor, and construction coordinators to internal staff ranging from head of engineering to the project manager. This composition was designed to mirror the dynamics of the supply chain and accurately represent the complexity and interdependencies inherent in its operations. For this research experts were selected based on their expertise in supply chain management and experience in off-site construction. The CEO of Metadecor provided support throughout the process of selecting and assessing whether each expert possessed sufficient knowledge to be considered an expert.

The success factors selection was conducted through one-on-one semi-structured interviews. Face-to-face interviews in real life were used in 8 out of 9 instances because they provided minimal time delay between posing a question and receiving a response. One interview was conducted in an online setting through video conferencing. This allowed the interviewer and interviewee to react promptly to each other's actions or statements in all one-on-one interviews. It enabled the interviewee to ask questions throughout the entire interview about factors and supply chain management when needed. However, this synchronous nature placed greater demand on the interviewer to maintain focus on both questions being asked and the responses provided (Opdenakker, 2006).

One member of this panel assessing relevance operated outside of Metadecor's supply chain and is employed by a yacht-building company. The shipbuilding sector, similar to the façade building sector, is classified as making ETO products, also employing a highly similar approach regarding their supply chain management (Montali et al., 2017). This particular company occupies a similar position in its supply chain as Metadecor does in theirs and creates highly unique yachts. Just as Metadecor, this company is classified as making pre-assembled products and having a modular supply chains (Pero et al., 2015). Both companies participate in interorganisational projects and manufacture highly customisable products. Although CSFs specific to this sector have not yet been identified, an expert within this company assessed the relevance of these factors and had the opportunity to suggest additional ones that are critical for a company specializing in ETO products. By incorporating an expert from the shipbuilding sector with an extensive depth of knowledge and proficiency in supply chain management, the list of CSFs became more comprehensive and aligned with the needs of Metadecor's supply chain. Appendix 2 presents the interview protocol for the Metadecor supply chain experts, while Appendix 3 details the interview protocol for the expert from the shipbuilding industry. This resulted in a list of success factors that combines those identified in the literature with those discovered in the field.

3.3.3 Expert-led ranking of success factors

Another panel was formed for ranking the success factors, this panel consists out of experts from the design phase to the realisation phase on-site. The composition of this panel mirrors that of the factor relevance panel, except for the participant from the custom shipbuilding company. Since they are not directly involved in Metadecor's supply chain, they could not contribute to the ranking of the factors. According to Sagir Ozdemir & Saaty (2015), the optimal jury size, where the weighted sum of errors is least, falls somewhere between six and eight. So there was chosen to form a panel with the jury size of eight, which is close to the optimal jury size. An expert was selected based on criteria such as education or years of experience (Ozdemir & Saaty, 2015). Once again, the experts were chosen based on their expertise in supply chain management and experience in off-site construction. Throughout the selection process, the CEO of Metadecor provided support, ensuring that each expert possessed the necessary knowledge to be considered an expert.

In AHP, judges can be given priorities, so the judgements of high-priority judges carry more weight. It enhances the influence of judges considered more knowledgeable (Ozdemir & Saaty, 2015). Liu et al. (2023), showed that assigning weights to decisionmakers in group decisions is an important research topic in AHP, this study also indicates that while this is an important topic, most existing studies oversimplify this process and use equal weights for every decisionmaker in the process. This issue has been seen in a range of studies (Kabak & Ervural, 2017; Kar, 2014; Koohathongsumrit & Chankham, 2023; Zhang et al., 2020). Not assigning weights to the decisionmaker could be suitable in certain circumstances, it is however not the right thing to do in complex problems (Liu et al., 2023). There exist two methods to assign weight to different experts, this could be done in a subjective or an objective way (Koksalmis & Kabak, 2019). In the subjective method, the weights are determined by a supra decisionmaker, or by the individuals inside the group who could evaluate each others expertise or capabilities (Liu et al., 2023). In the objective method, the weights are calculated based on the input data of the experts, like the similarity between experts' judgements (Van den Honert, 2001; Zhang et al., 2020). Both the subjective and objective methods have their cons. The objective method takes usage of one single characteristic of the input data of the expert, which is inadequate in a complex hierarchy. For the subjective method, it is necessary to consider that it relies heavily on the expertise of individuals, this could be a problem especially in professional evaluations such as assessing the safety of diversion tunnels (Liu et al., 2023).

For this research there is chosen to use the subjective method by Aly & Vrana (2008). As the CEO has contributed to the formation of the pairwise comparison panel and initiated contact with these experts, it is assumed that this person possesses sufficient knowledge and experience to assess their relative importance. This resulted in considering the CEO of Metadecor as the supra decisionmaker. A supra decisionmaker has a sufficient knowledge and experience to asses the relative importance of every expert. (Aly & Vrana, 2008). In addition to this, it was crucial for Metadecor that panellists remained unaware of each other's identities, as this could potentially impact Metadecor's competitive position.

There were three criteria considered to assess the experts' decision-making capabilities as defined by Aly & Vrana (2008).

- Knowledge. This criterion is defined as: "the amount of important knowledge and information each expert bears."

- Experience. This criterion is defined as: “the age and historical deepness of the expertise contained in each expert.”
- Relevance. This criterion is defined as: “the degree of how much each expert has knowledge pertaining and relating to the decision problem.”

The supra decisionmaker conducted the needed pairwise comparisons to eventually determine the final weights for each expert as a whole (Aly & Vrana, 2008). The identified success factors were compared pairwise, with each member of the panel individually and systematically assessing the relative importance of one factor over another. These comparisons were both achieved by employing a ratio scale consisting of nine distinct levels of importance intensity as suggested by Saaty (2012), shown in Table 1. These comparisons have both been done in the software called AHP-OS. A detailed description of this pairwise comparison process can be found in Appendix 4.

Table 1. The intensity of importance scale.

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
2	Weak importance	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus importance	
5	Strong importance	Experience and judgement strongly favour one over another
6	Strong plus importance	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong importance	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Note. Adapted from Models, Methods, Concepts & Applications of the Analytic Hierarchy Process by Thomas L. Saaty and Luis G. Vargas, 2012, International Series in Operations Research & Management Science 175, (p. 6)

3.3.4 Transitioning into a representative group judgement

The weighted scores for each success factor were calculated based on the pairwise comparisons. These scores represented the relative importance of each factor in the context of Metadecor's panelised construction supply chain. Additionally, the judgemental consistency of each expert was determined to ensure the reliability of expert judgements. This was done by defining the Consistency Ratio (C.R,). In general, a C.R. of 0.10 or lower when ($n \geq 5$) is considered acceptable. If the C.R. exceeds this threshold, it indicates a lack of judgemental consistency, and the relative importance assigned to each objective has to be re-evaluated and adjusted to enhance consistency. Defining the C.R. was done by comparing the Consistency Index (C.I.), with the appropriate number also called random consistency index (R.I.). R.I. represents the consistency index that would result from completely random assignment of judgement values (Saaty & Vargas, 2012). AHP-OS calculates the C.R. immediately after completing the pairwise comparisons and provides recommendations on how to reduce the C.R. below the threshold. This offers experts the opportunity to adjust their judgements to ensure consistent results (Goepel, 2022). The influence of judges considered more knowledgeable was enhanced by assigning greater weight to the judgements of high-priority judges. In this way the combination of the numerical judgements of the individuals was turned into a representative group judgement as outlined by Aczél & Saaty (1983). Appendix 5 contains the detailed calculations for aggregating the group judgement.

Once all of the pairwise comparisons were done. AHP-OS gave the choice between 10 different scales. Although there are no guidelines on what scale is best to use, research of Goepel (2018a) made a comparison between all scales, taking account the maximum number of criteria, weight boundary, weight uncertainty, weight ratio, and weight dispersion. These parameters have the following meaning:

- "Weight bound and weight ratio: What is the maximum weight for a judgement that one criterion is "9 - extreme more important" than all others, and how compare the total ratios of calculated weights for different scales?
- Weight uncertainty: How much depend the weights on small variations of the judgement?
- Weight dispersion: How are the weights distributed over the judgement range?" (Goepel, 2018a).

In Table 2, the scale comparison can be seen where the number of criteria $n = 2$ and the maximum number of criteria, n_{max} are shown with the judgement range from 1 to 9. There is made a distinction between three categories of scales based on their maximum entry value which is indicated as 'Weight Ratio' in Table 2, category 1 uses the maximum entry value of 9, where category 2 uses the maximum range lower than 9 and in category 3 scales with higher values than 9.

In this research, both the CSF hierarchy and the expertise assessment hierarchy utilize more than ten criteria, so there had to be made a choice between the four scales under category 3.

Table 2. Judgement scale comparison in AHP.

<table>
<tr><th rowspan="2">Cat</th><th rowspan="2">Scale</th><th rowspan="2">n_{max}</th><th colspan="2">Weight boundary %</th><th>Weight Ratio</th><th colspan="2">Max. Weight Uncertainty %</th><th colspan="2">Weight Dispersion %</th></tr>
<tr><th>$n = 2$</th><th>$n = n_{max}$</th><th>$n = 2$</th><th>$n = 2$</th><th>$n = n_{max}$</th><th>$n = 2$</th><th>$n = n_{max}$</th></tr>
<tr><td rowspan="4">1</td><td>Fundamental AHP</td><td rowspan="4">10</td><td rowspan="4">90</td><td rowspan="4">50</td><td rowspan="4">9</td><td>9.9</td><td>4.3</td><td>3.1</td><td>1.1</td></tr>
<tr><td>Inverse-linear</td><td>4.7</td><td>16</td><td>1.1</td><td>3.9</td></tr>
<tr><td>Balanced</td><td>2.5</td><td>7.8</td><td>0</td><td>2</td></tr>
<tr><td>Generalized balanced</td><td colspan="2">2.5</td><td colspan="2">0</td></tr>
<tr><td rowspan="3">2</td><td>Logaritmic</td><td rowspan="2">4</td><td>77</td><td>53</td><td>3.3</td><td>6.8</td><td>5.5</td><td>2.1</td><td>2</td></tr>
<tr><td>Root square</td><td>75</td><td>50</td><td>3</td><td>5</td><td>4.0</td><td>1.4</td><td>1.3</td></tr>
<tr><td>Koczkodaj</td><td>3</td><td>67</td><td>50</td><td>2</td><td>1.5</td><td>1.4</td><td>0.3</td><td>0.2</td></tr>
<tr><td rowspan="4">3</td><td>Power</td><td rowspan="4">≥10</td><td>99</td><td>90</td><td>81</td><td>19</td><td>11</td><td>6.2</td><td>3.6</td></tr>
<tr><td>Goemetric</td><td colspan="2">99.6</td><td>256</td><td>6</td><td>8</td><td>2.3</td><td>2.5</td></tr>
<tr><td>Adaptive</td><td colspan="2" rowspan="2">90</td><td rowspan="2">9</td><td>10</td><td>11</td><td>3.1</td><td>3.6</td></tr>
<tr><td>Adaptive-balanced</td><td>2.5</td><td>4.9</td><td colspan="2">0</td></tr>
</table>

Note. Reprinted from *Comparison of Judgment Scales of the Analytical Hierarchy Process — A New Approach by Klaus Goepel, 2018, International Journal of the Analytic Hierarchy Process 18, (p. 438)*

For the expertise assessment, there was chosen to select a scale which is less sensitive to the weight ratios. According to Salo & Hämäläinen (1997), the reference points on each criterion should be less preferred than the actual alternatives' achievement levels. As the questions that are normally asked in receiving preference information in AHP normally look like "Which of the alternatives, Mercedes or Honda, is better with respect to quality and by how much?" (Salo & Hämäläinen, 1997).

Salo & Hämäläinen (1997) proposed the balanced scale and sketched an example question which actually should be asked: "Which of the alternatives, Mercedes or Honda, gives the greater quality improvement over BadQualityCar (i.e. the poor-quality reference car)?' assuming that the reply is

Mercedes, `How many times greater is the quality improvement from BadQualityCar to Mercedes than the quality improvement from BadQualityCar to Honda?". This train of thought was applied in this research. Because all of the participants are seen as experts, the reference point was put as non expert. The decisionmaker should be asked: 'Which of the alternatives, expert 1, expert 2, gives greater expertise over a non expert (i.e. a participant which cannot be called an expert by the CEO of Metadecor)?' and assuming that the reply is expert 1 'how many times greater is the quality improvement from a non expert to expert 1 than the quality improvement from non expert to expert 2?' This implied that a balanced scale would be more appropriate for the expertise assessment. Since the 'Balanced scale' has a maximum number of criteria of 10, a corrected version of this scale called the 'Adaptive-balanced scale' has been used. This scale has been introduced in Goepel (2018a) and is also incorporated in AHP-OS. The generalised balanced and adaptive-balanced scales emerged as the most favourable options. They maintain consistent weight uncertainty throughout the entire range from 1 to 9, with uncertainties not surpassing 5% across up to ten criteria (Goepel, 2018a). For the CSF hierarchy, there is chosen for the geometric scale as Goepel (2018a) indicated that this scale used, made the discrimination between the priorities more significant. This resulted in a more precise ranking of the CSFs. Because the power scale has a much higher weight uncertainty and a higher weight dispersion, the geometric scale is favoured (Goepel, 2018a).

Eventually, a sensitivity and consensus analysis was done. The sensitivity analysis revealed the extent of influence the supra decisionmaker had on the final prioritisation by comparing the prioritisations with and without the expert weights. A consensus analysis was undertaken to determine if agreement could be reached among the decisionmakers prioritising the CSFs. Consensus, or homogeneity, is when a group of people come to a shared opinion or position, usually through agreement (Touimi, 2014). In a consensus, individuals are open to hearing different viewpoints rather than forcing a decision, and they engage in discussions that aim to benefit everyone. When half of the decisionmakers consider a CSF important while the other half do not, consensus on the most critical CSFs becomes unattainable. Consequently, it is imperative to analyse the group's outcome and establish a consensus or agreement on the most significant CSFs. This consensus analysis, achievable through AHP-OS, involved aggregating individual priorities using the arithmetic mean. This software uses a cluster algorithm based on the Shannon Entropy and Diversity theory which can identify possible subgroups with a higher consensus among the group of decisionmakers (Goepel, 2022).

3.3.5 Evaluation of current supply chain management level and linkage to theory

The concluding stage of the project attributed the linking of the prioritised CSFs to the theories discussed in the theoretical background. This process involved discussions with the company's CEO to understand why the most important CSFs were deemed the most important and to identify current development areas for Metadecor's supply chain management. This data was collected through a semi-structured interview, Appendix 6 presents the interview protocol for this discussion. Additionally, all the gathered raw data from the interviews conducted during the expert-led success factors selection and expert-led ranking of success factors phases were analysed to identify development areas for Metadecor's supply chain management. This data source triangulation ensured the reliability and validity of the findings, as the data was cross verified. These interviews supported the quick scan purchasing maturity tool presented in Bemelmans et al. (2013), this tool was used for an assessment of the purchasing maturity based on the purchasing development model described in Van Weele et al. (1998), which can give quick insights into the current level of maturity based on 20 characteristics shown in Appendix 1. These insights therefore revealed potential areas for enhancing the effectiveness of supply chain management at the case company. A detailed explanation of the purchasing development model described in Van Weele et al. (1998) and the quick scan purchasing maturity tool presented in Bemelmans et al. (2013) can be found in section 2.3.

4 Findings

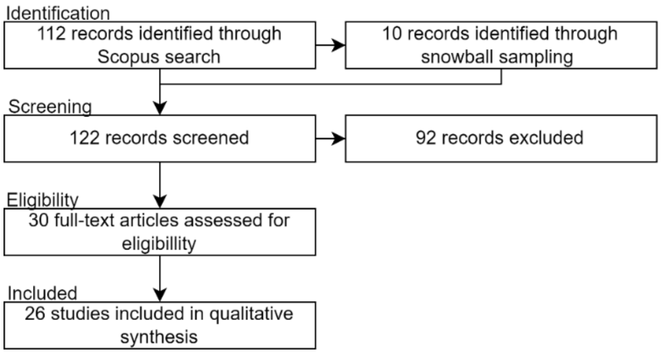
By leveraging data collected from the literature review, the factor relevance panel, and pairwise comparisons facilitated by both decisionmakers and the supra decisionmaker, we can systematically present and analyse all findings.

4.1 CSFs of supply chain management in off-site construction

Based on the data collected through the literature review, a list of CSFs for achieving effective supply chain management in off-site construction was developed. In Figure 9, it is evident that 112 records were identified through the Scopus search. Additionally, 10 records were discovered through backward snowball sampling by examining the references within the set of CSFs described in the records identified through Scopus. A total of 122 records were screened, and of these, 92 were excluded. Consequently, 30 full-text articles remained eligible for constructing the AHP hierarchy. In total, these studies contained 165 factors. Many of the factors on this list were duplicates or had almost identical meanings. This led to organizing the factors into five distinct subcategories, which simplified the structuring of the data.

- 'Forecast capacity'. This subcategory is defined as: "The predictive capability emphasises the supply chain's need for accurate forecasting of potential changes and challenges, facilitating proactive preparations" (Liu & Liu, 2023).
- 'Communication and collaboration'. Whereas communication can be defined as: "The transmission or exchange of information, knowledge, or ideas, by means of speech, writing, mechanical or electronic media, etc" (Oxford English, 2023). Collaboration can be defined as: "The act of working together with other people or organisations to create or achieve something" (Cambridge English, 2023).
- 'Robustness'. This subcategory is defined as: "Robustness is mainly considered as the ability of the system to continue to function well in the event of a disruption" (Vlajic et al., 2012).
- 'Adaptability'. This subcategory is defined as: "Adaptability ensures that the supply chain can adapt to evolving circumstances, and sustain its operations" (Liu & Liu, 2023).
- 'Sustainability'. This subcategory is defined as: "The idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment" (Cambridge English, 2023).

Figure 9. Literature review flow chart.



Note. Own work

The identified factors were compiled, categorised and merged to eliminate duplicates, a comprehensive list of CSFs for off-site construction was created. Some of these articles contained unique CSFs not found in any other studies, leading to their exclusion.

The category sustainability yielded initially two success factors, which were both cited one time. Therefore, this category should not have existed according to the methodology of the study. However, the effects of climate change on businesses are extremely serious and will greatly affect the economic sustainability of both developed and emerging countries (Rajeev et al., 2017). Arshad (2022) reported symbiotic factors which may direct the overall dynamics of the system by mitigating the negative impacts or boosting the positive effects in supply chain management of MiC. Here, the factor 'Promoting sustainability' was seen as a factor which had significant importance. Additionally, the construction industry is the largest global consumer of raw materials and is responsible for 25-40% of the world's total carbon emissions (Bühler et al., 2017). Given that sustainability is becoming increasingly important in supply chain management within the construction sector (Adetunji et al., 2008; Li & Lu, 2021), it seemed essential to assess the relevance of these CSFs in this subcategory for panelised construction by the panel of experts. 26 studies were included in the qualitative synthesis, yielding 21 unique CSFs spanning 5 subcategories. This hierarchy is formed likewise as similar previous studies (Agha et al., 2012; Gudienė et al., 2014; Wang et al., 2017). The 21 CSFs are defined and detailed in the following sections, with references for all CSFs provided in Appendix 7.

4.1.1 Forecast capacity success factors

'Extensive project planning' (CSF1), involves planning the supply chain elements, with continuous monitoring for replanning and rescheduling activities (Arshad & Zayed, 2022). During this planning stage, experts from various fields collaborate to gather important design information aimed at making manufacturing more efficient and promoting circularity benefits (Wuni & Shen, 2020a). This planning phase holds significant importance in prefab projects, as its success can greatly affect the overall outcome of the project. From a circular perspective, thorough planning is crucial because each stage of the supply chain and its associated construction processes has a distinct impact on the environment (Wuni & Shen, 2022). Then there is 'risk management' (CSF2) which is a system designed to recognise and assess all potential risks that a business or project may encounter. This allows for informed decisions on how best to address and mitigate these risks. The extent of risks associated with design projects heavily relies on the design team's comprehensive understanding of the design process and the origins of potential risks (Zou et al., 2007).

4.1.2 Communication and collaboration success factors

'Information sharing' (CSF3) is described as: "a set of activities by which information is provided to others, either proactively or upon request, such that the information has an impact on another person's (or persons') image of the world … and creates a shared, or mutually compatible working, understanding of the world" (Savolainen, 2017). Zhang (2021), proposed exploring more ways to communicate effectively between construction and management teams to make work more efficient. 'Effective use of information and communication technology' (CSF4) like building information modelling (BIM), achieves this goal by providing advantages for construction supply chains. These tools effectively aid in information sharing and decision making analysis (Lu et al., 2022). A Building Information Model is described by the National institute of Building Science as: "The digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards" (NIBS, 2017). Another CSF: 'early involvement of critical stakeholders' (CSF5) shows that in prefabricated prefinished volumetric construction projects, it's crucial to commit early to the approach to gain all its advantages. The construction stakeholder theory suggests there are many people involved in construction projects. Successfully managing these people in modular construction projects means identifying them early, planning how to work with them, getting them involved, and making sure any risks related to meeting their expectations from the project are controlled (Wuni & Shen, 2020b). An 'active involvement of key participants throughout the project' (CSF6) is also seen as a CSF. According to Wuni (2020), Key stakeholders such as owners, designers, vendors, and contractors play a crucial role in modular construction projects, remaining actively involved at every stage of the process. Involving a fabricator during the design stage, for instance, facilitates the establishment of early relationships and enhances comprehension before production commences. The participation of owners and contractors in both the design and fabrication phases enables them to understand technical aspects of the value chain, thereby encouraging a supportive environment for project implementation through a fully integrated approach. ‘Coordination of offsite and onsite work packages’ (CSF7). This factor is defined by Zhang (2023) as: “coordination among design, production, and construction.” It's been observed that the success of modular construction projects heavily relies on effectively coordinating the interconnected supply chain phases both before and during construction. Planning and controlling these projects require strategies to organise, synchronise, and oversee supply chain stages and stakeholders for a smooth project completion (Wuni & Shen, 2020a). ‘Avoidance of dysfunctional conflicts’ (CSF8). Effectively managing stakeholder conflicts arising from diverse requirements, expectations, and interests is crucial in modular construction projects. Effective leadership constitutes proactively identifying these conflicts and developing measures to mitigate their potential impact on the success of stakeholder management (Wuni & Shen, 2020b). ‘Closer Relationship with partners with collaboration’ (CSF9). Every stage of the supply chain contributes to the entirety. Should a single stage encounter an issue, it can disrupt or dismantle the entire supply chain. Improving inter-company communication through initiatives like frequent team-building exercises and reciprocal visits fosters trust and enhances the capacity for mutual aid and collaboration, thereby improving the resilience of the supply chain (Zhang et al., 2021). A closer relationship with partners could stimulate competition among organisations. For instance, a partnership between a main contractor and a subcontractor might drive both parties to compete in acquiring new skills and enhancing their products and processes. These short-term alliances are created in order to strive for short-term project or business related benefits (Love et al., 2002). ‘Creating long-term partnerships with trust’ (CSF10). One step further than closer relationships with collaboration is based around building mutual trust among the various entities engaged in the supply chain. Which fosters the development of enduring and cooperative partnerships with essential stakeholders (Lönngren et al., 2010). Love et al. (2002), distinguished two types of alliances in the construction industry, namely short-term and long-term. Where the short-term partnerships are more based around collaboration and the long-term partnerships are based around cooperation. These long-term partnerships are built upon synergistic relationships in order to develop core competencies. This cooperation creates a reflective and mutual learning environment, encouraging effective knowledge sharing.

4.1.3 Robustness success factors

‘Adequate knowledge and good contractor leadership’ (CSF11), is defined as the overall ability or capability of a general contractor to effectively manage and oversee prefabricated or modular building projects (Zhao et al., 2022). The supply chain encompasses numerous procedures and participants, presenting challenges in management due to intricate tasks and significant resource allocation. This intricacy leads to alterations within the supply chain and exposes the limitations of stakeholders in governing workflows efficiently (Luo et al., 2020). ‘Selecting competent and experienced key players’ (CSF12) is described as utilizing a skilled team of specialist managers. Proficient leadership from a specialised main contractor and engaging capable project participants are imperative for minimizing inefficiencies, eliminating redundancies, and enhancing productivity throughout the supply chain (Wuni & Shen, 2023). Contractors need to evaluate the core competencies and capabilities of each supplier and consider their potential for replacement. Given that firms may exit the market for diverse reasons, contractors should be ready to establish alternative partnerships accordingly (Benton & McHenry, 2010). ‘Standardised factory-made components’ (CSF13) can be delineated as prefabricated construction complexity arises from assembling individual components, crucial for safety. Non-standardised parts complicate assembly, making it costlier and time-consuming. Standardizing components simplifies manufacturing and assembly (Zhao, 2021). Low standardisation could lead to compatibility issues, particularly when there are multiple manufacturers involved in a project. Especially in prefabricated façade development, where incompatibility is identified as a critical issue (Gan et al., 2018). ‘Quality assurance and quality control’ (CSF14) is also seen as a CSF. The modular construction supply chain faces disruption when defective materials are rejected. To prevent this, it's crucial to implement a comprehensive quality assurance and quality control strategy along with a strong performance measurement system across the entire modular construction supply chain (Hussein & Zayed, 2021). 'Inventory management and control' (CSF15). Coordination between on-site and off-site operations are challenging, especially in terms of scheduling deliveries (Blismas, 2007). To attain the objectives of modular construction, effective management and oversight of resources, such as materials and equipment, are indispensable (Wuni & Shen, 2022).

4.1.4 Adaptability success factors

The prefabricated building supply chain is a complex network of relations consisting of multiple stages and multiple subjects, and the scale and complexity of these are increasing. Therefore 'Low supply chain response time' (CSF16) is seen as a critical factor, which is defined as the market change response time, and the ability to quickly recover from a disruption to an ideal state. Which is a requirement in an environment where the disturbances both upstream and downstream in the supply chain have increased significantly. Aspects that influence the response time are the adaptability of the design of the components, the managerial proficiency of component factories and the expertise of on-site construction personnel (Zhang et al., 2023). 'High logistics support level' (CSF17) encompasses various indicators, including the arrangement of routes, transport capacity, and route count (Lu et al., 2022). In off-site construction a large amount of on-site work is transferred to factories. Although there is a shorter construction period than traditional construction methods, there are extra parts transportation processes (Zhao et al., 2022). To reduce the shortages of modules on the location which could result in additional costs and changes to schedules, just-in-times delivery arrangements are relevant practices regarding the logistics support level (Wuni & Shen, 2022). Besides this, the reliability of logistics firms is seen as a factor that influences the resilience of off-site construction supply chains (Zhang et al., 2023). A 'High manufacturing capability' (CSF18) is the performance of the modules manufacturer. This encompasses the fabricator experience, their facilities, and capabilities in modules design and production (Wuni & Shen, 2020a). Since off-site construction projects rely heavily on manufacturing capability due to the need for numerous factory-made components, factories with large capacities are essential to ensure timely project completion (Zhao, 2021). 'Multi-component manufacturer supply' (CSF19) is defined as having a high number of potential manufacturers who are able to produce various prefabricated parts. According to Zhang (2021), this increases the redundancy of the supply chain. The adoption of multiple suppliers protects manufacturers against uncertainty in supply and demand, which reduces the reliance on a single source, improves the responsiveness of suppliers, and increases the competition between suppliers to enhance the quality and innovation (Arashpour et al., 2017).

4.1.5 Sustainability success factors

For the subcategory 'sustainability' there is made a distinction between 'integrate circular economy principles into the supply chain' (CSF20), and 'promoting sustainability' (CSF21). Whereas CSF20 is seen as integrating principles of the circular economy in the supply chain. Which could be seen as maximizing the material reuse, recycling, and recovery, while also minimizing the waste generated (Wuni & Shen, 2022). CSF21 is more seen as creating a mutual understanding of the need to adopt sustainable practices and, encourage sustainability practices such as waste minimisation, energy conservation, and the adoption of recycling (Arshad & Zayed, 2022). Table 3 shows for every factor the papers which have been cited.

4.2 CSFs of supply chain management in panelised construction

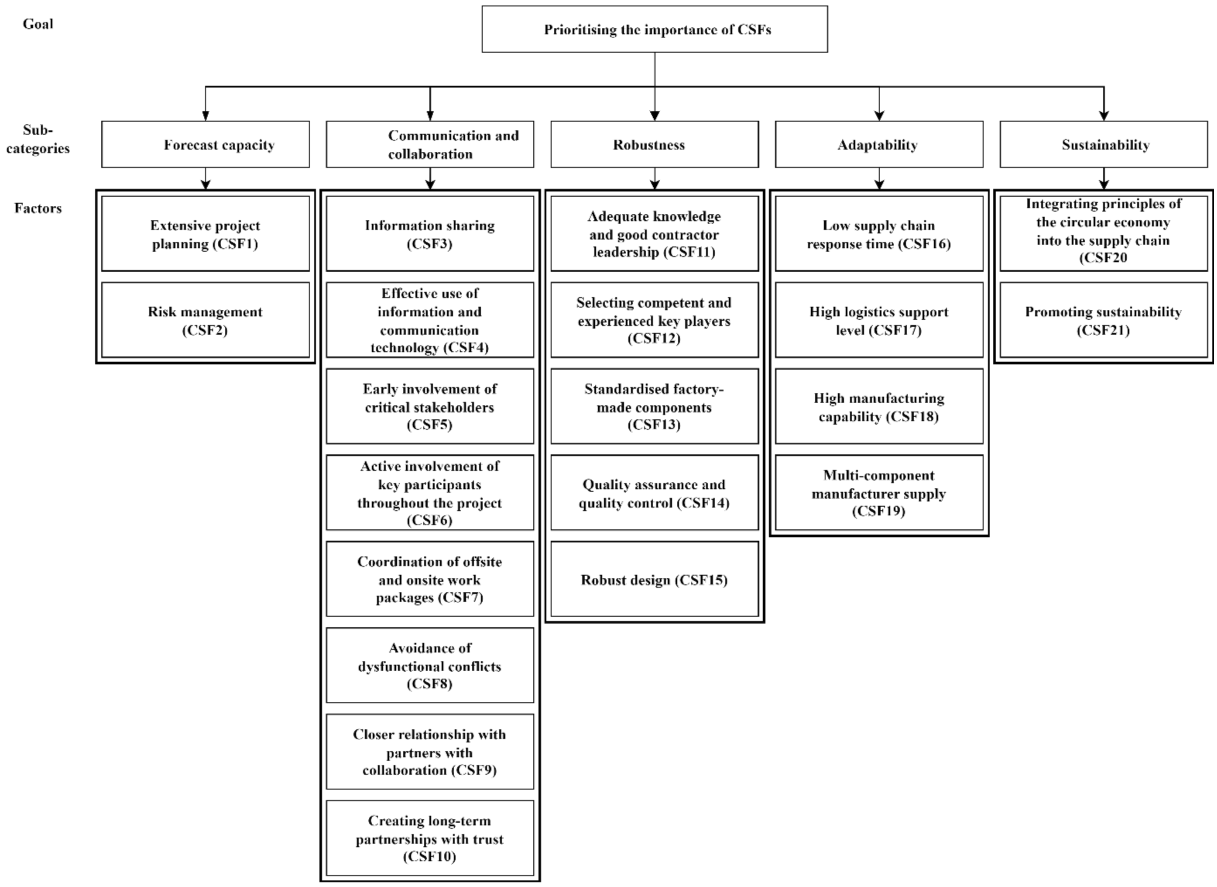
Most of the off-site construction CSFs could be directly transferred to panelised construction. However, nine experts, both internal and external to Metadecor, identified several non-critical success factors in the list of off-site construction success factors for a panelised construction supply chain. Every expert regarded the success factors underneath the subcategory ‘forecast capacity’, ‘communication and collaboration’ as CSFs. So, CSF1 till CSF10 were regarded as CSFs for effective supply chain management in panelised construction. This was also the case for CSF11 and 12 in the subcategory ‘robustness’. Some experts did not consider 'standardised factory-made components' (CSF13) as relevant. Specifically, three out of the nine experts did not classify it as a CSF. Notably, two of these experts were external to Metadecor. Despite this minority view, the majority of the panellists still deemed CSF13 as essential, which let to the inclusion of this factor.

The factor 'inventory management and control' (CSF15) was deemed irrelevant by five experts, four of whom were directly employed at Metadecor. Consequently, this CSF was excluded from the research. The primary reasons for the exclusion were the nature of creating unique projects, resulting in minimal inventory at Metadecor. Panellists noted that each project is unique, leading to minimal stock. The perspectives on this factor provided by some interviewees were as follows. The shipbuilding supply chain expert stated: *“Also, I believe that inventory management and control are not crucial in an engineer-to-order supply chain.”* The internal logistics expert commented: *“We produce custom-made products. I value standardisation, and through standardisation, you may accumulate more inventory, which could become important eventually, but not at the moment.”* The internal construction expert remarked: *“That one can be dispensed with. Because we create unique projects, we have almost no inventory. With us, it's different every time, so we have minimal stock.”*

One of the panellists suggested an additional factor for the subcategory ‘robustness’ which was a ‘robust design’. The majority of the panellists regarded this factor as a CSF, so this led to the inclusion of this factor. In consultation with the panellist who suggested the factor, this factor was placed in the subcategory ‘robustness’ as a replacement for CSF15. A similar factor was found in the literature called “Design for manufacture, assembly, and circular economy” this factor was not put in the draft hierarchy because it was observed once as a CSF in off-site construction. In the literature this factor was described as the need for a specialist contractors to possess technical expertise in various areas, including design for manufacture and assembly, design for circular economy, tolerance management, connection systems, production engineering, and value engineering (Wuni & Shen, 2022). After consulting with experts, it was decided to broaden this factor based on their suggestions, particularly by incorporating an early design freeze. The concept of an early design freeze was also referenced once in the literature. This practice is viewed as timely approval of designs, a prerequisite for advancing to the subsequent stage of the supply chain, namely, module fabrication, which is categorised as the production in this study (Wuni & Shen, 2020a). Eventually by submerging these two definitions, the definition for the new factor ‘Robust design’ (CSF15) was created: ‘Creating a precise design that considers manufacturing and assembly processes, tolerance management, connection systems, production techniques, and value engineering, the importance of which lies in establishing it early in the process (Wuni & Shen, 2020a; Wuni et al., 2022).’

In the 'adaptability' subcategory, various factors were seen as non-critical by different panellists, this was also the case for the findings in the 'sustainability' subcategory. However, the majority of the panel

Figure 10. AHP hierarchy of CSFs for achieving effective supply chain management in panelised construction.



Note. Own work

considered the factors within both 'adaptability' and 'sustainability' as critical, leading to the inclusion of all these CSFs. In Figure 10 the AHP hierarchy is shown with the inclusion of the new factor ‘robust design’ and the exclusion of the factor 'inventory management and control'. In this hierarchy all CSFs for achieving effective supply chain management in panelised construction are shown with their corresponding subcategory. Table 3 shows the references from literature for all CSFs.

Table 3. References from literature for CSFs in panelised construction.

NO	SUCCESS FACTOR NAME	REFERENCES
CSF1	Extensive project planning	Luo *et al.* (2020) Arshad & Zayed (2022) Wuni & Shen (2022) Wuni *et al.* (2020) Wuni & Shen (2020b) Hussein & Zayed (2021) Wuni & Shen (2020a)
CSF2	Risk management	Arshad & Zayed (2022) Bevilacqua *et al* (2018) Wuni *et al.* (2020) Hussein & Zayed (2021) Aloini *et al.* (2012) Lu *et al.* (2022) Zhang *et al.* (2023) Liu & Liu (2023) Wuni & Shen (2020b)
CSF3	Information sharing	Zhang & Li (2023) Wuni & Shen (2020b) Cano *et al.* (2015) Wuni & Shen (2020a) Zhang & Ji (2021) Zhang *et al.* (2023) Bevilacqua *et al.* (2018) Aloini *et al.* (2012) Zhao *et al*. (2022) Lönngren *et al.* (2010)
CSF4	Effective use of information and communication technology	Wuni *et al.* (2020) Liu & Liu (2023) Aloini *et al.* (2012) Zhang *et al.* (2021) Wuni & Shen (2020b) Zhang *et al.* (2023) Lu *et al.* (2022)
CSF5	Early involvement of critical stakeholders	Wuni & Shen (2020b) Aloini *et al.* (2012) Wuni *et al.* (2020)
CSF6	Active involvement of key participants throughout the project	Wuni & Shen (2020b) Wuni *et al.* (2020) Wuni & Shen (2020a)
CSF7	Coordination of offsite and onsite work packages	Vrijhoef (2000) Wuni & Shen (2020a) Wuni & Shen (2020b) Wuni *et al.* (2020) Zhao *et al*. (2022) Cano *et al.* (2015) Zhang *et al.* (2023) Arshad & Zayed (2022) Luo *et al.* (2020) Wuni & Shen (2022) Wuni & Shen (2023) Aloini *et al.* (2012) Lönngren *et al.* (2010)
CSF8	Avoidance of dysfunctional conflicts	Wuni & Shen (2023) Wuni & Shen (2020b) Aloini *et al.* (2012)
CSF9	Closer relationship with partners with collaboration	Bevilacqua *et al.* (2018) Zhang *et al.* (2021) Riazi *et al.* (2019) Zhang *et al.* (2023) Cano *et al.* (2015) Wuni *et al.* (2020) Lönngren *et al.* (2010)
CSF10	Creating long-term partnerships with trust	Vrijhoef (2000) Lönngren *et al.* (2010)

CSF11	Adequate knowledge and good contractor leadership	Zhao *et al*. (2022) Wuni & Shen (2020b) Luo *et al.* (2020) Wuni & Shen (2020a)
CSF12	Selecting competent and experienced key players	Wuni & Shen (2023) Aloini *et al.* (2012) Zhao *et al*. (2022)
CSF13	Standardised factory-made components	Zhao (2021) Aloini *et al.* (2012) Zhao *et al*. (2022)
CSF14	Quality assurance and quality control	Zhao (2021) Cano *et al.* (2015) Wuni & Shen (2020a) Zhang *et al.* (2023)
CSF15	Robust design	Wuni & Shen (2020a) Wuni & Shen (2022)
CSF16	Low supply chain response time	Zhang *et al.* (2023) Zhao *et al*. (2022) Liu & Liu (2023)
CSF17	High logistics support level	Lu *et al.* (2022) O'Connor et al. (2014) Zhao *et al*. (2022) Wuni & Shen (2020a) Wuni *et al.* (2019) Zhang *et al.* (2023) Wuni & Shen (2022)
CSF18	High manufacturing capability	Wuni & Shen (2020a) Zhao (2021)
CSF19	Multi-component manufacturer supply	Zhang *et al.* (2021) Zhang *et al.* (2023) Arashpour et al. (2017)
CSF20	Integrating principles of the circular economy in the supply chain	Wuni & Shen (2022)
CSF21	Promoting sustainability	Arshad & Zayed (2022)

Table 4 presents a graphic showing the critical and non-critical success factors as perceived by participants. The column headers represent experts from various stag es of the Metadecor supply chain, with an additional supply chain expert included from the shipbuilding sector. The row headers display the different CSFs.

Table 4. Factor relevance rating, criticality of success factors.

	Design Internally	**Design Externally**	**Production Internally**	**Production Externally**	**Logistics Internally**	**Logistics Externally**	**Construction Internally**	**Construction Externally**	**Shipbuilding supply chain expert**
CSF 1 - CSF 12									
CSF13	X			X					X
CSF14									
CSF15	X		X		X		X		X
New CSF15					X				
CSF16									
CSF17			X						X
CSF18					X			X	
CSF19		X		X					X
CSF20	X		X						X
CSF21	X		X						X

Legend	
	Critical factor
X	**Non-critical factor**

Note. Own work

4.3 Prioritisation of CSFs in panelised construction for complex façade manufacturing

The results of the pairwise comparisons conducted by both decisionmakers and the supra decisionmaker, let to the prioritisation of the 21 CSFs tailored to panelised construction. Table 5 displays the C.R. for all judgements made by the decisionmakers on the CSFs. The results indicate that each participant's judgements remained consistent, as all ratios fell below the 10% threshold. This demonstrates that the judgements are consistent enough to be able to produce reliable results (Saaty & Vargas, 2012).

Table 5. Consistency Ratios for all decisionmakers in CSFs ranking.

C.R. overview						
Experts	**Subgroup categorisation**	**Forecast capacity**	**Communication and collaboration**	**Robustness**	**Adaptability**	**Sustainability**
Design Internally	5.8%	0.0%	9.2%	9.5%	3.2%	0.0%
Design Externally	8.5%	0.0%	9.6%	6.2%	5.8%	0.0%
Production Internally	7.8%	0.0%	7.9%	7.1%	9.1%	0.0%
Production Externally	8.4%	0.0%	9.3%	5.7%	4.4%	0.0%
Logistics Internally	4.3%	0.0%	9.2%	3.8%	9.2%	0.0%
Logistics Externally	4.4%	0.0%	9.9%	7.1%	8.5%	0.0%
Construction Internally	9.3%	0.0%	9.1%	9.7%	5.2%	0.0%
Construction Externally	6.8%	0.0%	7.8%	2.0%	1.2%	0.0%

Note. Own work

The eight panellists were ranked based on three judgement criteria. All of the judgements for the pairwise comparisons were first entered using the intensity of importance scale. In Table 6 can be seen that the criteria 'relevance' that is "the degree of how much each expert has knowledge pertaining and relating to the decision problem" (Aly & Vrana, 2008), was valued twice as important as each of the other criteria. This indicates that this criterion has a relatively higher level of importance according to the supra decisionmaker. Previous research found similar results (Aly & Vrana, 2008; Rosidin et al., 2024).

Table 6. Consolidated decision matrix of subcategories in expertise assessment.

	Knowledge	**Experience**	**Relevance**	**Priority vector**
Knowledge	1	1	0.5	0.25
Experience	1	1	0.5	0.25
Relevance	2	2	1	0.5

Note. Own work

As Table 7 depicts, the results of the expertise assessment by the supra decisionmaker can also be seen as consistent as the C.R. of all the judgements of the judgement criteria are below the threshold of 10% (Saaty & Vargas, 2012). This makes it feasible to combine the judgements on the expertise of the decisionmakers and the relative importance of the CSFs.

Table 7. Consistency Ratios of supra decisionmaker.

C.R. overview				
Category	**Subgroup categorisation**	**Knowledge**	**Experience**	**Relevance**
C.R.	0.0%	3.8%	6.1%	6.5%

Note. Own work

The supra decisionmaker regarded three decisionmakers as having substantially more expertise in supply chain management in panelised construction than others in the panel. Namely the production internal with 19.32% of the total weight, the construction internal expert with 23.15%, and the construction external expert with 18.97% of the weight. These three experts had a combined weighting of 72.86%. The supra decisionmaker also regarded that there was more expertise internally then externally, as the experts internally had a combined weighting of 64% and the experts externally 36%. The weights assigned to the different experts can be seen in Table 8.

Table 8. Weights assigned to the decisionmakers.

Expert	Expert weight
Design Internal	8.77%
Design External	8.35%
Production Internal	19.32%
Production External	7.72%
Logistics Internal	7.65%
Logistics External	6.07%
Construction Internal	23.15%
Construction External	18.97%

Note. Own work

In Table 9 the aggregated result can be seen. In this table the combined result of the expertise assessment and the CSF ranking is presented alongside their corresponding subcategories, including percentages, rankings, and average subcategory ranking. As Rockhart (1979), indicated that a typical CSF list yields four to eight CSFs, the 8 CSFs with the highest weight were seen as the most important ones. This selection corresponds to a threshold of 5% in the total factor weighting.

Table 9. Aggregated CSF prioritisation.

Corresponding subcategory	Critical Success Factors	Percentage	Ranking	Average subcategory ranking
Adaptability	**Low supply chain response time (CSF16)**	**11.43%**	**1**	6
	Multi-component manufacturer supply (CSF19)	**8.82%**	**4**	
	High logistics support level (CSF17)	**8,78%**	**5**	
	High manufacturing capability (CSF18)	2.27%	15	
Communication and collaboration	**Active involvement of key participants throughout project (CSF6)**	**10.59%**	**2**	11
	Early involvement of critical stakeholders (CSF5)	**6.18%**	**6**	
	Coordination of offsite and onsite work packages (CSF7)	**5.56%**	**7**	
	Effective use of information and communication technology (CSF4)	4.25%	10	
	Creating long-term partnerships with trust (CSF10)	3.05%	13	
	Closer Relationship with partners with collaboration (CSF9)	2.41%	14	
	Information sharing (CSF3)	2.19%	16	
	Avoidance of dysfunctional conflicts (CSF8)	1.21%	20	
Robustness	**Robust design (CSF15)**	**9.10%**	**3**	12
	Adequate knowledge and good contractor leadership (CSF11)	**5.40%**	**8**	
	Selecting competent and experienced key players (CSF12)	3.30%	12	
	Quality assurance and quality control (CSF14)	2.02%	18	
	Standardised factory-made components (CSF13)	1.77%	19	
Forecast capacity	Risk management (CSF2)	3.79%	11	14
	Extensive project planning (CSF1)	2.18%	17	
Sustainability	Integrating circular economy principles into the supply chain (CSF20)	4.97%	9	15
	Promoting sustainability (CSF21)	0.73%	21	

Note. Own work

The final prioritisation shows that ‘low supply chain response time’ (CSF 16) has received 11.43% of the total weighting which results in making this the most important factor in achieving effective supply chain management for a complex façade manufacturer according to the ranking. ‘Active involvement of key participants throughout the project’ (CSF6) received 10.59% of the total weighting which makes this the second most important factor. ‘Robust design’ (CSF15), receives 9.10% of the weighting which makes this the third most important factor. When talking about the subcategories, sustainability is seen as the least important subcategory, with an average weight of 2.85%. ‘Adaptability’ is seen as the most important subcategory with an average weight of 7.83%.

4.4 Validation of prioritised CSFs

According to the group results without expert weights attached, the following ranking of importance can be compared with the prioritisation that includes expertise weights, shown in Table 10. Although sustainability is still seen as the least important subcategory and 'adaptability' is seen as the most important subcategory, the ranking of importance differs substantially.

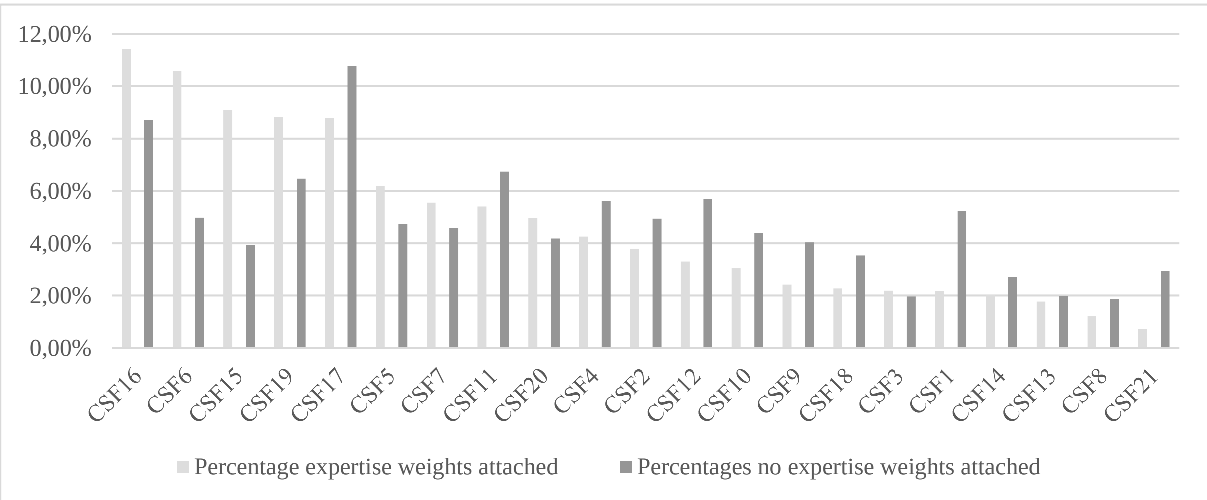
Table 10. Comparison of CSF factor weightings with and without expert weights attached.

Corresponding subcategory	CSFs prioritization with expertise incorporated		CSFs prioritization without expertise incorporated	
Adaptability	**Low supply chain response time (CSF16)**	**1**	**High logistics support level (CSF17)**	**1**
	Multi-component manufacturer supply (CSF19)	**4**	**Low supply chain response time (CSF16)**	**2**
	High logistics support level (CSF17)	**5**	**Multi-component manufacturer supply (CSF19)**	**4**
	High manufacturing capability (CSF18)	15	High manufacturing capability (CSF18)	16
Communication and collaboration	**Active involvement of key participants throughout project (CSF6)**	**2**	**Effective use of information and communication technology (CSF4**	**6**
	Early involvement of critical stakeholders (CSF5)	**6**	**Active involvement of key participants throughout project (CSF6)**	**8**
	Coordination of offsite and onsite work packages (CSF7)	**7**	Early involvement of critical stakeholders (CSF5)	10
	Effective use of information and communication technology (CSF4)	10	Coordination of offsite and onsite work packages (CSF7)	11
	Creating long-term partnerships with trust (CSF10)	13	Creating long-term partnerships with trust (CSF10)	12
	Closer Relationship with partners with collaboration (CSF9)	14	Closer Relationship with partners with collaboration (CSF9)	14
	Information sharing (CSF3)	16	Information sharing (CSF3)	20
	Avoidance of dysfunctional conflicts (CSF8)	20	Avoidance of dysfunctional conflicts (CSF8)	21
Robustness	**Robust design (CSF15)**	**3**	**Adequate knowledge and good contractor leadership (CSF11)**	**3**
	Adequate knowledge and good contractor leadership (CSF11)	**8**	**Selecting competent and experienced key players (CSF12)**	**5**
	Selecting competent and experienced key players (CSF12)	12	Robust design (CSF15)	15
	Quality assurance and quality control (CSF14)	18	Quality assurance and quality control (CSF14)	18
	Standardised factory-made components (CSF13)	19	Standardised factory-made components (CSF13)	19
Forecast capacity	Risk management (CSF2)	11	**Extensive project planning (CSF1)**	**7**
	Extensive project planning (CSF1)	17	Risk management (CSF2)	9
Sustainability	Integrating circular economy principles into the supply chain (CSF20)	9	Integrating circular economy principles into the supply chain (CSF20)	13
	Promoting sustainability (CSF21)	21	Promoting sustainability (CSF21)	17

Note. Own work

This shows that the end ranking is rather sensitive to the judgement of the supra decisionmaker. Figure 11 depicts the comparison between the ranking without the expert weights attached and the ranking with the expert weights attached with the percentages included. The biggest difference can be seen at 'active involvement of key participants throughout the project' (CSF6), where there is a weight drop of 5.61%. Also, 'robust design' (CSF15) has a weight drop of 5.18%. 'Extensive project planning' (CSF1) has the biggest weight increase with 3.06%. 'Selecting competent and experienced key players' (CSF12) has the second biggest weight increase with 2.39%. Appendix 8 shows the precise percentages of the final rankings, both with and without the expertise weighting differences included. Of the top eight most important CSFs according to the ranking with the incorporated expertise weights, five remained in the ranking without the expertise weight. None of the CSFs occupy the same ranking position in both prioritisations.

Figure 11. Comparison of ranking with and without expertise attached.



Note. Own work

The relative homogeneity shows the consensus of the judgements of the decisionmakers in the CSF ranking. The consensus scale ranges from 0 to 100%, where 0% indicates that there is no consensus, and every judgement of all the decisionmakers are completely distinct, 100% indicates that they are all identical (Goepel, 2022). The fundamental AHP scale shown in Table 1 and incorporated in AHP-OS, is used to compute the consensus. The relative homogeneity without the clustering is 72.7%. This indicates that the consensus is moderate. Because the group consensus of the whole group is higher than 70%, AHP-OS indicates that clustering is not required, and the result can be seen as reliable (Goepel, 2022). With 88% of the participants, so excluding one decisionmaker out of the group, this relative homogeneity increases to 77.6%, making the consensus high (Goepel, 2022). When changing the threshold to attain a consensus above 87.5%, only 38% of the decisionmakers remain, which is equivalent to 3 individuals. This results in a relative homogeneity of 90.7%. The combined expertise weight of the 3 decisionmakers in this cluster is 58.42%. In Table 12 the wording scale for AHP consensus indicator can be seen.

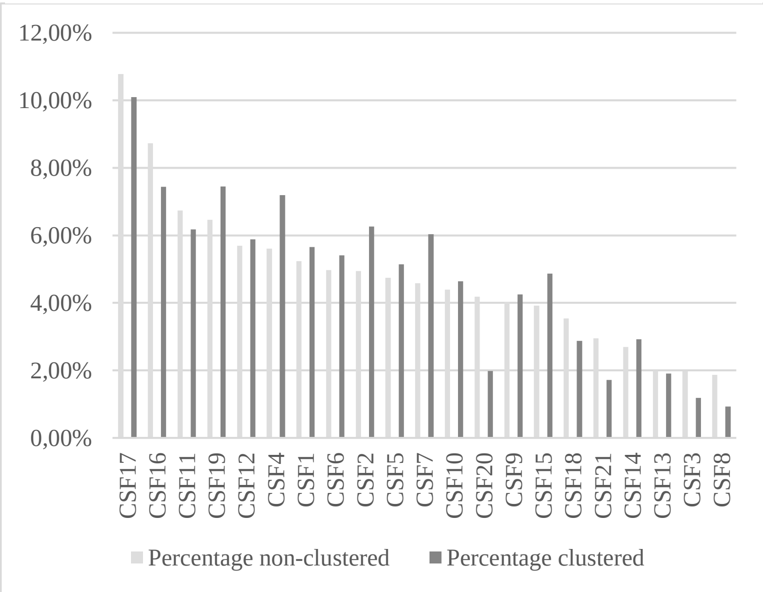
Table 12. Wording scale for consensus indicator.

Consensus S_{AHP}	**0%...50%**	**50%...62.5%**	**62.5%...75%**	**75%...87.5%**	**87.5%...100%**
Wording scale	very low	low	moderate	high	Very high

Note. Reprinted Group Consensus Cluster Analysis using Shannon Alpha- and Beta Entropy *by Klaus Goepel, 2022*

Although clustering is not required, Figure 12 compares the rankings without a cluster and no expertise weight assigned to the rankings of the panel, with the rankings that include a formed cluster with a consensus of 77.6%, considered high and also no expertise weight assigned. Both comparisons are based on the weighted geometric mean aggregation of individual judgements, computed by AHP-OS. There can be seen that there is a slightly more dispersion between the top 8 most important factors of the non-clustered ranking. With a standard deviation of 1.87% as opposed to 1.29% in the top 8 CSFs. The top 8 ranking for the non-clustered and no expertise differentiation group was slightly different as can be seen more detailed in appendix 9. In distinguishing between the two rankings of the top 8 most important factors, two factors stand out distinctly. CSF1 and CSF6 are exclusive to the non-clustered group and absent in the clustered group. Conversely, CSF2 and CSF7 are unique to the clustered group but absent in the non-clustered group. Furthermore, the biggest weight difference can be seen for CSF20 which got a weight of 4.18% in the non-clustered group and a weight of 1.98% in the clustered group, which is a difference of 2.2%.

Figure 12. Comparison of ranking between clustered and non-clustered group.



Note. Own work

While there is a difference of opinion on which CSFs are most important, the group consensus of 72.7%, exceeding the 70% threshold, and the fact that decision-makers with very high consensus received the majority of the expertise weight, indicate that the final ranking can be considered reliable.

4.5 Current supply chain management level and theoretical linkages

This section examines the interview findings, focusing on the rationale behind the CSFs in supply chain management for panelised construction as explained by Metadecor's CEO and panellists inside the supply chain of the case company.

Metadecor handles highly specialised and complex prefabrication projects, such as those in Zuidwolde and Rotterdam. Prefabrication has emerged as a critical strategy to streamline construction processes and minimise on-site assembly time. For instance, a project in Rotterdam, despite its erratic design and urban location, benefited from prefabrication by reducing the complexity and time required on-site: "*A project in Rotterdam was complex because of its location, and it is an erratic design. ... It's a bit of a strange shape, and it's in an urban area*." Similarly, a project in Zuidwolde, with its intricate shape and numerous components, underscored the necessity of prefabrication to avoid time-consuming and labour-intensive on-site assembly: *"Zuidwolde has a special shape and contains many parts. If you do not prefab this, it will cost a lot of time on the construction site."* The interviewee highlighted that a robust design and active involvement of key players are paramount in ensuring project success in these cases: *"If you look at robustness of the design and active involvement of key players, these are the most common points in these projects."*

Neglecting certain CSFs, such as project planning and risk management, can detrimentally impact project success. For example, inadequate project planning can lead to unclear timelines and responsibilities, causing project delays and inefficiencies. It was emphasised that maintaining a comprehensive project plan from the outset is crucial to avoid such issues. Some CSFs, such as information and communication technologies, risk management, and quality control, were deemed less critical in the context of prefabrication. These factors, while still critical, are considered general project management practices that apply across all types of projects, not just those involving prefabrication. The interviewee noted that these elements are always necessary, regardless of the construction method employed: *"You must always create and maintain a project plan. I notice that with any type of project, if a plan is not made at the start of the project, it can then break down because it is not clear when an engineer should start. When I look at the less important factors, these are things that are generalities that you need to do, not lose sight of."* The purchasing processes at Metadecor reflect a dynamic approach that is currently evolving towards a more coordinated and strategic model. The company operates with a collaborative framework involving various roles such as construction coordinators, project leaders, and a buyer. While lacking a dedicated purchasing manager, this decentralised structure allows for flexibility and adaptability in procurement decisions. The product groups are coordinated on a central level and are centrally negotiated by the buyer. Although a clear strategy isn't formulated according to standard procedures, or formal decision processes: *"I don't think we have purchasing that works very clearly according to a specific strategy ... Only the buyer actually negotiates the price, he usually does not go into such depth."*

A notable shift in purchasing strategy is evident, moving away from a singular focus on obtaining the lowest price. Over the past two years, Metadecor has embraced a more nuanced approach, prioritising quality and capacity alongside cost considerations. This strategic shift is exemplified by recent procurement decisions, where orders were strategically divided between suppliers based on their capabilities to ensure optimal outcomes: *"We do not have a purchasing manager, the role is divided among a construction coordinator, project leader and a buyer… We have been moving away from focusing solely on the lowest price for some time now. I think it's been around 2 years now…We are trying to take the step towards coordinated purchasing so that we can ensure that the capacity of producers is matched to what we need."* The expert working at the construction stage internally, indicated that the internal procedures with the corresponding information and communication technologies were well integrated and developed, using the ERP system and the BIM models *"BIM is the order of the day. We have our own ERP system. When materials are purchased, it indicates where something is and where it needs to go. For example, when the panels are made and they need to go to* *the coater, it will show something like 'April 10, it will be ready,' and transport is scheduled for it to go to the coater. All of this is tracked in the ERP system."* Metadecor also demonstrates a strong commitment to supplier engagement and collaboration, as evidenced by their proactive approach to pre-production planning. Despite encountering suppliers with deficiencies in planning capabilities, the company actively assists them in improving their processes. By engaging in regular planning sessions and setting clear expectations, the company tries to build a collaborative environment aimed at enhancing supplier performance and ensuring alignment with project timelines and objectives: *"Pre-production planning for example, we have a number of suppliers who are not very good at their own planning. We then help them to make the planning, and when we take them through it every week, expectations can be set."* But there gets acknowledged that there is still room for improvement for this collaboration with the suppliers: *"I think there is room for improvement in knowing what a supplier can do and spreading your work accordingly."* The same perspective is shared by the external panel member from the production stage. Who stresses the fact that being informed as extensively as possible is critical. When asking about the factors which are specifically relevant to the collaboration with the supplier there was acknowledged that the degree of automation and digitisation was of utmost importance: *"It is very important to draw 3D models in sheet metal step files. There is still quite a bit of fragmentation, although progress has been made at Metadecor".* There is stated that there is still room for improvement in the external integration: "*Every construction coordinator does this in his own way, which means that during the start-up period, before everything is processed by our construction coordinator and before production is started, you are much too busy with the drawings".* The external expert from the production stage highlighted the fact that this integration could be improved in the standardisation of the departmental procedure of the buyers, which could be achievable through digitisation according to the expert. This same train of thought is shared by the external expert working at the logistics stage in Metadecor's supply chain. Who indicated that efficiency could be improved through more optimal workflow of the various construction coordinators, particularly in terms of monitoring when tasks are completed and ensuring better external coordination: *"At Metadecor, we do have a bit of an issue regarding the coordination of when something is ready and when it should be transported, which is quite challenging because we deal with production and assembly…Information should be shared earlier…Efficiency could be improved here by combining more tasks, creating organisation within our company and allowing for more efficient driving…it would be more convenient to have better coordination with each other. Perhaps having a point of contact would be helpful, something that Metadecor probably has some thoughts on as well."*

When focusing on the 4 stages of the research namely, design, production, logistics, and construction. There becomes acknowledged that the integration of the logistics stage could be improved. As the 'High logistics support level' (CSF17) was seen as one of the most important factors for achieving effective supply chain management. The full potential is not yet fully leveraged. While the design stage receives considerable attention, the logistics stage often falls short. This gap is particularly noticeable in the transition from production to assembly and then to the construction site: "*I think we can still improve a lot in the logistics stage. Just looking at the coordination of offsite and onsite work packages, this largely has to do with logistics… But what we especially notice is that the supply from to the assembly and the supply to the construction site still leaves its mark."*

Taking these answers to the development model described in Van Weele et al. (1998) which can be seen in Figure 5. It seems that the company is mostly operating in Stage 3 and 4, which is the 'Co-ordinated Purchasing' and the 'Internal integration cross-functional purchasing', adapting tactical purchasing as there purchasing function. As Metadecor has been moving away from solely focusing on the lowest price and has started considering factors like quality and capacity. It becomes evident that it has outgrown the operational purchasing function of stage 2 'Commercial orientation; lowest unit price'. An ad hoc approach is also not the case at Metadecor as there are taken proactive actions towards suppliers to support their work. The CEO recognised that there is a decentralised purchasing structure, where the goods where centrally negotiated by the buyer, which further confirms the coordinated tactical purchasing structure. There was pointed out that there exist cross-functional purchasing teams. With an extensive use of integrated information systems and technologies used internally. However, the CEO indicated that processes weren't standardised and formalised throughout the organisation, which shows that a clear strategy isn't formulated according to standard procedures or formal decision processes. Although there was acknowledged that Metadecor assists in the planning activities of the suppliers in certain projects, the company recognises the need to better understand the capabilities of their suppliers and allocate work accordingly. There is still a gap between the internal integration to the external integration with suppliers. Where the supplier base optimisation is slowly getting more attention.

5 Discussion

This chapter delves into the study's findings, answering the sub research questions which will eventually lead towards an answer to the central research question: 'How do CSFs regarding supply chain management contribute to achieving effective supply chain management in panelised construction for a complex façade system manufacturer?' The theoretical and practical implications will then be discussed. At last, we address the study's limitations and provide recommendations for future research.

5.1 Discussion of main findings

A complex façade system manufacturer operates in a collaborative and multidisciplinary environment, with the creation of intricate and detailed façades, where the level of the customer involvement is high. Although the complexity of projects differs, where the activities in these projects range from unique to repetitive, the outcome of each project is distinctive. The increased total variability in these projects, with high demands for cooperation and coordination in the design, planning, and installation of the structures, necessitates effective supply chain management to fully leverage the advantages of off-site construction. The supply chain in off-site construction projects is longer compared to traditional construction projects, because are more production steps involved in the construction process. Generally, in off-site construction coordinating different aspects of the project are required rather than a step-by-step approach seen in regular construction. For a complex façade system manufacturer adopting panelised construction this is also the case. The findings of this study shed light on the CSFs essential for effective supply chain management in panelised construction. Rockhart indicated that the CSFs are: *"the few key areas where 'things must go right' for the business to flourish an for the managers goal to be attained" (Rockart, 1979)*. These factors help the focusing of management attention on the critical areas of business, and also gives an understanding of the priority areas of a business. These CSFs could be specifically tailored to business processes, projects and strategies (Cooper, 2009).

5.1.1 CSFs in off-site construction supply chain management

Although the CSFs for effective supply chain management in panelised construction were till thus far unknown, there is an extensive amount of literature available on the CSFs for effective supply chain management in of other types of off-site construction. Therefore, this study went into the CSFs specifically for panelised construction by assessing the relevance of CSFs found in the literature of other types of off-site construction. This resulted in a list of in total 165 potential CSFs relevant to panelised construction. By merging factors and excluding factors which were underrepresented in the literature a list of 21 CSFs remained. These CSFs ranged across five categories: 'forecast capacity', 'communication and collaboration', 'robustness', 'adaptability' and 'sustainability'.

5.1.2 CSFs for a complex façade system manufacturer using panelised construction

The 21 CSFs of achieving effective supply chain management for other off-site construction methods formed the basis for identifying factors relevant to panelised construction. To assess the relevance of the CSFs, a panel of experts was formed. This panel included experts from the case company's supply chain, which adopts panelised construction for the creation of their complex façade systems, as well as a supply chain management expert from the custom shipbuilding sector. As there was indicated that the façade industry had particularly similarities regarding supply chain management with the shipbuilding sector (Montali et al., 2017). This resulted in that each CSF was defined and supported by relevant literature, as well as identified as CSFs by a panel of experts. By letting the opinion of the majority count, a list of CSFs tailored to panelised construction could be compiled. Not all CSFs were directly transferable to the panelised construction as inventory management and control was not seen as critical enough to be deemed as an CSF. On the other hand, a robust design was seen as more critical by the experts than the literature would suggest, which let to the inclusion of this CSF.

5.1.3 Overall prioritisation of importance of the CSFs of effective supply chain management for a complex façade system manufacturer using panelised construction

The AHP methodology assisted in prioritising the success factors which were deemed as the most important ones. To achieve this a hierarchy was made aimed to provide a structured approach for prioritising CSFs in panelised construction supply chain management at the case company. Through pairwise comparisons using the AHP of the relevant CSFs a final ranking could be achieved. The examination of expertise among the panel members by a supra decisionmaker enriched the analysis, highlighting key individuals with substantial knowledge and experience. The hierarchical assessment provided insights into the relative importance of different experts, informing the weighting process and enhancing the accuracy of the findings. Furthermore, the consensus analysis revealed a moderate consensus, although the identification of a high-consensus cluster underscored areas of agreement among experts. The research saw that CSFs corresponding to the subcategory ‘adaptability’ were overall seen as the most important with 3 out of 4 CSFs coming out of this subcategory as the 8 most important CSFs. The 8 CSFs with the highest importance in this research were a ‘low supply chain response time’ (CSF16) an ‘active involvement of key participants throughout the project’ (CSF6), a ‘robust design’ (CSF15), a ‘multi-component manufacturer supply’ (CSF19) a ‘high logistics support level’ (CSF17), ‘early involvement of critical stakeholders’ (CSF5), ‘coordination of offsite and onsite work packages’ (CSF7) and, ‘adequate knowledge and good contractor leadership’ (CSF11). Factors related to forecasting and sustainability were seen as less important inside the supply chain of the complex façade manufacturer when using panelised construction.

5.1.4 Supply chain management development potential at the case company

The purchasing development model described in Van Weele et al. (1998) addressed the fact that in order to achieve supply chain management external integration is needed with collaboration with supply partners. The maturity assessment tool in Bemelmans et al. (2013) assisted in assessing where the case company was at in their development towards effective supply chain management. First an internal collaboration has to be present to work towards an external collaboration with suppliers to reach an external integration or supply chain management. As there has been moving away from solely focusing on the lowest price, it seems that the company is mostly operating in Stage 3 and 4, which is the ‘Co-ordinated Purchasing’ and the 'Internal integration cross-functional purchasing', adapting tactical purchasing as there purchasing function. However, the purchasing function does not have standardised and formalised processes implemented throughout the case company, which indicates that the company is stuck in the second stage which is the ‘Commercial orientation; lowest unit price’. This indicates that the supply chain management could be significantly improved at Metadecor. As there was indicated that the distinctive structures made with panelised construction gives customers enhanced influence in the supply chain (Montali et al., 2017), the need for an external integration becomes evident. By implementing more standardised and formalised purchasing processes, external collaboration with partners may be improved.

5.1.5 Final conclusion

As Rockhart (1979) indicated, the CSFs could help organisations to achieve a specific goal, as they were the few key areas which had to go right for the business to achieve their goals. Improving the performance of the CSFs could help reaching effective supply chain management. However, it may not be feasible to target or improve all the 21 CSFs identified in this study. The eight most important CSFs may therefore serve as a starting point for developing an effective panelised construction supply chain. Improving the performance of the most important CSFs specifically for effective supply chain management tailored to panelised construction may result in achieving effective supply chain management. So, the study suggests that in order to achieve effective supply chain management, an extensive communication and collaboration with external partners have to be present. Where the critical stakeholders are involved early in the process and key participants are actively involved throughout the project cycle. The study may also imply that in panelised construction, improving the supply chain's adaptability to changing conditions while maintaining its functionality is crucial for success.

5.2 Theoretical implications

The outcome of this research enriched the existing literature on supply chain management in off-site construction by the identified CSFs specific to panelised construction and the determination of which factors of these are the most important. Before this research the CSFs for effective supply chain management in panelised construction were unknown. Through a literature review regarding the success factors of off-site construction combined with expertise from experts working in panelised construction and supply chain management, this study has looked into which success factors are critical in achieving effective supply chain management. As the size of the panelised construction research is relatively small (Hussein et al., 2021; Zaalouk, 2023). Other similar research on the success determinants for supply chain management in MiC projects indicated that there were nine critical success determinants (Wuni & Shen, 2023). Table 11 shows the rankings of the panelised construction CSFs with the rankings of the success determinants for MiC, where the top nine success determinants were seen as critical success determinants. The factors prioritised in Wuni et al. (2023) are categorised into the subcategories used in this research.

Table 11. Comparative table of supply chain management success factors: Panelised construction vs. MiC.

Corresponding subcategory	CSFs panelised construction		Success determinants MiC ranking	
Adaptability	**Low supply chain response time (CSF16)**	**1**	Hedging and transport delay avoidance	20
	Multi-component manufacturer supply (CSF19)	**4**		
	High logistics support level (CSF17)	**5**		
	High manufacturing capability (CSF18)	15		
Communication and collaboration	**Active involvement of key participants throughout project (CSF6)**	2	**Effective communication and information sharing**	**2**
	Early involvement of critical stakeholders (CSF5)	**6**	**Seamless integration and coordination of supply chain**	**4**
	Coordination of offsite and onsite work packages (CSF7)	**7**	**Early involvement of critical supply chain stakeholders**	**5**
	Effective use of information and communication technology (CSF4)	10	**Effective coordination and management of stakeholders**	**7**
	Creating long-term partnerships with trust (CSF10)	13	**Improved interfaces between offsite and onsite work packages**	**8**
	Closer Relationship with partners with collaboration (CSF9)	14	Collaborative procurement system and contracting	11
	Information sharing (CSF3)	16	Information and communication technology solutions	13
	Avoidance of dysfunctional conflicts (CSF8)	20	Managing disruptions, disturbances and failure points	14
			Managing complex stakeholder relationships and networks	15
			Long-term relationship and partnership	16
			Managing and avoiding dysfunctional supply chain conflicts	19
Robustness	**Robust design (CSF15)**	**3**	**Design for supply chain management**	**1**
	Adequate knowledge and good contractor leadership (CSF11)	**8**	**Organizational readiness and familiarity with MiC**	**3**
	Selecting competent and experienced key players (CSF12)	12	**Engaging competent and experienced key players**	**9**
	Quality assurance and quality control (CSF14)	18	Top management support and commitment	10
	Standardized factory-made components (CSF13)	19	Competent specialist management team	12
			Adequate resources and funding	17
			Effective leadership of a specialist contractor	18
Forecast capacity	Risk management (CSF2)	11	**Extensive project planning**	6
	Extensive project planning (CSF1)	17		
Sustainability	Integrating circular economy principles into the supply chain (CSF20)	9		
	Promoting sustainability (CSF21)	21		

Note. Adapted from *Exploring the critical success determinants for supply chain management in modular integrated construction projects by Ibrahim Yahaya Wuni and Geoffrey Qiping Shen, 2023, Smart and Sustainable Built Environment 12(2), (p.268)*

What can be perceived from the prioritised list is that they are mostly in the field of communication and collaboration. Similar studies yielded comparable findings, highlighting the importance of information sharing and collaboration for effective supply chain management in off-site construction (Arshad & Zayed, 2022; Cano et al., 2015; Liu & Liu, 2023; Luo et al., 2020). While my study identified three factors underneath the subcategory 'Communication and collaboration' as highly important. The subcategory 'adaptability' emerged as the most crucial. In contrast, Wuni's research did not reveal any critical success determinants in this particular field. We have seen that panelised construction made usage of an engineer-to-order supply chain, which resolved around the concepts of variability and uncertainty (Akinc & Meredith, 2015; Barbosa & Azevedo, 2018). Bertram (2019) noted that modular construction tends to exhibit more standardised practices compared to panelised construction. There was also indicated that panelised construction has a heightened customer involvement which adds complexity to the supply chain (Cigolini et al., 2022; Hussein et al., 2021). This might clarify the high importance of adaptability in supply chain management of panelised construction. As it could allow the company to navigate through the changing conditions it might face. This study may suggest that effective supply chain management strategies must be tailored to the specific characteristics of each construction method present, as there seems to be a difference between CSFs identified in other off-site construction methods.

5.3 Practical implications for the case company

Metadecor aimed to optimise their supply chain management but were unsure how to achieve this. The CSFs supported the process of finding out which key areas were of highest importance in supply chain management for a complex façade manufacturer using panelised construction. As there were CSFs available for other types of off-site construction but not for panelised construction specifically. The study aimed to understand which CSFs were the most important to achieve an effective supply chain management in panelised construction. The purchasing development model shown in Van Weele et al.

(1998), showed where the company was at regarding their development towards effective supply chain management. This research suggests that being agile and being able to adapt quickly to the changing environment is important in a supply chain which is full of variability where projects are all distinctive as in panelised construction. As there has been an observed rising complexity and scale of construction projects, the inefficient materials handling and control could be minimised by effective supply chain management (Wang et al., 2017). It may be concluded that complex façade manufacturers who adopt this category of off-site construction benefit more from adaptability, which could ensure responding effectively to changes and keep a competitive edge in the market. The case company operates mostly at stage 3 or 4 according to the purchasing development model shown in Van Weele et al. (1998). Where there is still a gap between the internal and external integration needed in order to reach effective supply chain management. Although the case company is actively seeking to achieve supply chain management, there are still characteristics that have not been met to do so effectively. The processes aren't formalised at the moment which is an prerequisite in order to achieve effective supply chain management. There could be worked towards formal complaint procedures, policies, and decision processes to use when approaching suppliers. In addition, there could also be worked towards standardised processes on the selection of suppliers. As was indicated by the study, supply by a broad range of suppliers was seen as an important CSF, formalised processes could make it feasible to achieve such. This formalisation may assist both segmentation, which serves as the analytical foundation for identifying the most critical suppliers, product groups, and supplier base optimisation, which leverages this information to streamline and enhance the procurement process. Both processes are interdependent, with segmentation informing the supplier base optimisation and vice versa. Meanwhile, this formalisation could assist in a more formal consultation structure on purchasing, which could assist in a way so that the purchasing plan is well implemented within the organisation. The KPI's at the case company could assist in this manner, which could be broadened by conducting regular audits of suppliers which could ensure that there is compliance with the quality and standards needed. This could be a first step in extending internal collaboration, allowing internal multidisciplinary teams to evolve in a way that fosters more developed external collaborations. Since the involvement of key stakeholders and participants was identified as an important CSF, developing the information and communication technology externally, could play a crucial role in facilitating their engagement and participation. As Zhang et al. (2023) that in order to improve the adaptability of the supply chain there should be a focus on the information technology application level. This involves implementing integrated information systems that link across the entire supply chain, involving not only the owner and subcontractors, as in the existing BIM models, but also multiple-tier suppliers. This may enable the owner of the project to better be able to effectively manage and oversee the whole project, which was seen as an important CSF. This may optimise the information exchange process between the different supply chain stakeholders, which would enable the case company to work towards the value chain integration. Where there are formally aligned plans with suppliers about the future regarding objectives, technologies, and strategies.

5.4 Limitations

The limitations of this study include various elements that might affect the thoroughness and applicability of the results. This study only included success factors which were seen as critical twice in literature, besides the CSFs related to sustainability. Incorporating a more diverse set of CSFs from the literature might increase the time required for the study. As a broader list of factors would necessitate a more thorough evaluation process, including relevance testing and scoring by experts. However, this comprehensive approach could potentially enhance the overall comprehensiveness of the study. Besides this, experts may have been inclined to prioritise CSFs which are relevant to this specific supply chain in their pairwise comparisons. The CSF 'information sharing' was included as a factor in this study, it emerged as a moderate important CSF according to the experts' assessments, coming in at place 10. This finding contrasts with previous research in the field of off-site construction, such as the results shown in Wuni and Shen (2023), which identified information sharing as one of the most critical CSFs in

Modular integrated Construction. The reason information sharing wasn't seen as important might be because the company has outgrown these factors. Consequently, the relative importance assigned to information sharing in this study may not fully capture its importance in facilitating effective supply chain management for all organisations using panelised construction, as every organisation is different. The external validity of these findings and their applicability to other complex façade manufacturers or other organisations using panelised construction, may therefore be limited. Also, some factors in the CSF list might constitute dependencies. For example, among the CSFs, information sharing and integrating communication technologies, the CSF integrating communication technologies might have an effect on the quality of information sharing. This interplay between CSFs could mean that factors regarded as less important may actually be more significant than the prioritised list in this research suggests. When looking at the sampled individuals, the experts in the clustered group with a consensus of 90.07%, got a combined weighting of 58.42% assigned by the CEO. This might indicate a bias towards a particular group's perspective or preferences and might overlook valuable insights and alternative viewpoints from other experts. This could be problematic if the group is not representative of the broader population or if their interests do not align with the overall objectives of the research. However, this research adopted a panel of experts from the four supply chain stages, with four experts working externally for the case company and four experts working internally. This was done to improve generalisability, and to ensure an optimal decision-maker panel size of six to eight as indicated in Ozdemir & Saaty (2015).

5.5 Recommendations for future research

Panelised construction is the least studied off-site construction method in comparison with prefabricated components- and modular construction (Hussein et al., 2021; Zaalouk, 2023). As the study may suggests that panelised construction needs other supply chain management strategies as opposed to other more standardised off-site construction techniques, future studies could focus more on the supply chain in panelised construction. Given the importance of adaptability in this subcategory of off-site construction, future research could be conducted across various projects and companies that adopt panelised construction. Each project still has a different supply chain because every project is considered unique (Azambuja & O'Brien, 2008). Consequently, CSFs can vary per project, and their importance may also differ (Kronbichler et al., 2009). Therefore, it is recommended to conduct further research to investigate the effect of adaptability in other supply chains where panelised construction is used, and to compare this with other supply chains where other methods of off-site construction are used. This research may imply that there are other dynamics within the supply chain of panelised construction, highlighting the need for optimisation frameworks specifically developed for supply chain management in this particular field. Focussing less on optimizing long-term relationships with suppliers and focussing more on the allowance of dynamicity inside the supply chain. Like, diversifying supplier sources and technologies that enable real-time visibility throughout the supply chain. Further research could also go into information systems in the construction sector which link not only the client with the main and subcontractors, but also with the suppliers, moving towards an integrated supply chain management. Since relationships in the construction sector are relatively short and not all interconnected, further research on blockchain-integrated supply chain management information systems could be beneficial, with a focus on anonymity in the supply chain. Further, the AHP method used in the study was an adaption of the method shown in Goepel (2018b) and Aly & Vrana (2008) incorporating the aggregation technique presented in Zhang (2020). Although this particular method can be seen as rigorous and robust, the literature showed a lack of detailed methods which could be used to transform the individual judgements and the weightings of decisionmakers into an aggregated group opinion. As seen in previous papers this critique about the AHP method is seen more (Kabak & Ervural, 2017; Zhang et al., 2020). Most of the papers show the results of the study but don't show the methods used to come to an end result. As Goepel, (2018b) indicated, the use of the specific calculation methods ensure that various requirements are met in order to achieve valid results. Many papers do not address the reliability and validity of their methods, raising concerns about the credibility of their findings and conclusions. It is therefore recommended to develop comprehensive methodology papers detailing the different AHP methods present, including its mathematical prerequisites. These papers should provide guidance and practical insights into implementing the AHP method. By doing so, future studies utilizing AHP can achieve greater validity and reliability, thereby ensuring the creation of meaningful results. In dealing with the dependencies and dynamic relationships which could be present between the CSFs, further CSF research could adopt the Analytical Networking Process method to prioritise CSFs. By using the ANP method, which is another Multi Criteria Decision Making method by Saaty, similar to AHP, the possible dependencies between different factors could be taken into account. Hence, future research could emphasise the comparability of factors in assessing the importance of CSFs through Multi Criteria Decision Making method studies. Although the factors underneath the sustainability subcategory were seen as a relatively less important in this study, green supply chains are becoming increasingly important (Adetunji et al., 2008; Li & Lu, 2021). Further research could therefore focus on how to balance the relationship between sustainability factors while still focusing on achieving the main goals in the supply chain of construction projects of time, quality, and cost. Lastly, given the increasing importance of sustainability and the potential significance of other factors, it is recommended to reevaluate the CSFs periodically. The relative importance of CSFs may change over time, and new CSFs may emerge due to evolving conditions and future developments.

5.6 Concluding remarks

This study aimed to answer the central research question: ‘How do CSFs regarding supply chain management contribute to achieving effective supply chain management in panelised construction for a complex façade system manufacturer?’ A list of CSFs specifically tailored to panelised construction were ranked for a complex façade system manufacturer. The ranking showed that areas are of importance were on adaptability, communication and collaboration and robustness inside the supply chain of panelised construction. This study concludes that effective supply chain management strategies may need to be tailored to the specific characteristics of each construction method present, as there seems to be a difference in importance between CSFs identified in other off-site construction methods.

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Appendix 1. 20 characteristics of the quick scan purchasing maturity tool shown in Bemelmans et al. (2013)

"Operational purchasing. Within the company, the main focus is on the timely availability of the correct materials and products for the primary process. As such, the purchasing function performs a clerical and administrative role and there is no clear policy on purchasing. Based on this, the main indicator of the performance of the purchasing function is the undisturbed progress of the company processes. For that reason, price and availability are the main factors in the selection of suppliers.

Tactical purchasing. The purchasing function is becoming an important part of the company, resulting in a situation where it is used as a knowledge centre for information about suppliers and the supplier market. Due to this, on a project level, multidisciplinary involvement comes into existence. Purchasing models/tools, such as the Pareto analyses and portfolio analysis, are used to optimise the supplier base and for the development of product group objectives. The purchasing function begins to have a strategic role, which results in a general purchasing strategy.

Strategic purchasing. Within the company, the purchasing function plays an essential role in the decision-making process. One of the reasons for this is that most of the purchases by the company are based on the total cost of ownership principle. Alongside this, there is also a differentiated strategy in place for every product group in order to optimise the supplier base and to maximise the performance of the right amount/type suppliers. The strategy is evaluated continuously and the strategy development process is frequently improved.

Decentralisation. There is little or no coordination and/or cooperation between the different functions and projects within the company. Due to this, purchasing plans are established by the purchaser exclusively for each specific project. Nevertheless, there is an autonomous purchasing department in place, albeit one that does not participate in the management team.

Coordination. Major strategic product groups are coordinated on a central level and are centrally negotiated and purchased through central contracts. Coordination and cooperation also exist between the different projects and functions within the company. This results in internal optimisation of the requirements' planning and scheduling process on a project level. In realizing this, it is important that the purchasing plan is well communicated to key internal stakeholders.

Centralisation. The structure of the purchasing function is "centre-led", i.e. the purchasing policy and the organisation of the purchasing processes are determined centrally. Here, the corporate purchasing policy is used as a guide for the individual product group plans, and this will result in a purchasing plan. To support the product group managers, a steering group is in place which leads the teams and coordinates the decision-making between the teams. In order to make effective use of the knowledge of suppliers, there are development initiatives for selected/qualified suppliers such that they can become (strategic) corporate suppliers.

Internal collaboration. Cross-functional purchasing teams are in place on a company-wide or divisional level, and this is combined with a formal consultation structure on purchasing. As examples of the benefits, this can result in cost reduction opportunities or can contribute to the harmonisation of suppliers. The purchasing plan is well implemented within the organisation since it is deployed through intensive discussions and approval in multidisciplinary teams. To assure the effective use of multidisciplinary teams, there is a reward and recognition plan that is to an extent related to team performance.

External collaboration. Cross-organisational teams (buyer and supplier) are established to realise continuous improvement of the operational process. In this way, the supplier contributes to value creation and to the competitive position of the company. Further, there are strategy meetings between the management and the supplier to align processes and to stimulate the development of new products/processes. All these actions result in an open-book policy with the supplier that involves sharing cost calculations and cost breakdowns for the entire value chain and which goes beyond the project level.

Multidisciplinary. As an addition to internal and external collaboration, this characteristic is focused on spreading the purchasing function throughout the organisation. This will lead to a multidisciplinary performance appraisal and decision-making process.

Segmentation. Purchasing models are used to distinguish commodity/product groups and to identify strategic suppliers. Cost models are used to select suppliers and to improve cost structures. Based on the information available, multidisciplinary teams are used to develop product group strategies and goals for strategic purchases within the company.

Supplier base optimisation. The number of suppliers is reduced substantially to realise an efficient purchasing function through the use of optimal supplier selection processes. To assure a transparent optimisation of the supplier base, information is communicated to suppliers and multidisciplinary teams are involved in these processes.

Reactive actions. An ad hoc approach, which results from a reactive mentality of the key internal stakeholders, exists within the company. Crisis-related decision and implementation processes for in- and out-sourcing, and basing the integration of suppliers in the operational process on gut feelings are good examples of the consequences of this approach.

Proactive actions. Formal, structured and documented processes exist within the organisation, and the employees share a commercial mentality. Further, measurement data are available which, in combination with knowledge on internal and external requirements, make it possible to take adequate actions towards suppliers.

Formalisation. Processes are standardised and formalised throughout the organisation in order to realise a professional purchasing function. Among other things, this can lead to formal complaint procedures, formal policies, formal decision processes and a formal documented supplier-selection process.

Integrated IS/IT. Extensive use of integrated IS/IT systems is made, providing the overall purchasing organisation with all the necessary data that originate in both internal and external sources. Further, the IS/IT systems are linked across the full supply chain, involving multiple-tier suppliers and customers, in order to facilitate information exchange and so reduce throughput time and development costs.

Performance indicators. An advanced integrated set of performance indicators is in place on the corporate level to measure, for example, supplier performance. Periodically, these results are compared with purchasing targets in order to develop the purchasing function and as input for future purchases.

Developed purchasing workforce. Trained and dedicated employees are available for the purchasing function and are selected for the competencies and technical knowledge that are necessary for a professional organisation. Personal development plans are in place, including individual training and career planning, to realise continuous development of the workforce. It is also necessary for the purchasing professionals to have a broad management orientation, which is assured through active career planning across functional disciplines.

Purchasing plans. Within the purchasing department, officials are appointed to formulate purchasing objectives and there is some specialisation of the workforce based on product segmentation. This results in clear purchasing objectives for projects and for the different product groups. These are laid down in purchasing plans which include detailed project purchasing budgets for the financial year.

Integrated strategy. Here, the purchasing organisation is fully aligned with the company's policy, objectives and structure. Within the company, this results in an integrated purchasing and company strategy which is laid down in formal reports available throughout the organisation.

Gain and risk sharing. Together with suppliers, there is a formal alignment of mutual future plans in the fields of technology, objectives and strategies. Further, information on future products, technology roadmaps, costs and customers is shared openly. To stimulate this, there is a formal organised incentive programme to solicit cost reduction ideas from suppliers (e.g. profit and gain sharing contracts, supplier suggestion programmes, idea rewarding)" (Bemelmans et al., 2013).

Appendix 2. Interview protocol experts from Metadecor's supply chain

Introduction

Hello, my name is Aaron. I am conducting this interview as part of a research study into the Critical Success Factors of effective supply chain management. The purpose of this interview is to gain insights into which success factors are crucial for the supply chain of panelised construction. All information you share will be anonymised. To give you a clearer understanding of the context of the research, which includes prefabricated construction and the concept of supply chain within this context, I have prepared a PowerPoint presentation.

I will be recording the interview from now on. Do you have any questions before I do this?

General questions, assessment of factor relevance

1. Have you been able to review the list of success factors I sent you? If so, do you have any comments or feedback?

2. Are there any additional factors that you consider important for a company operating within the panelised construction supply chain, or do you consider this list complete?

3. Do you believe there are additional factors specifically relevant to your collaboration with Metadecor, or do you consider this list complete?

4. Do you think some success factors are not critical success factors?

Assessment of factor prioritisation

You are seen as an expert in prioritising critical success factors. You are asked to rate the importance of these critical success factors, which are initially assessed for relevance. Try to get an overview of the entire supply chain, but don't forget to consider your perspective on the collaboration between your stage in the supply chain and Metadecor's overall supply chain. Your stage in the supply chain is defined by the CEO of Metadecor as the DESIGN/PRODUCTION/LOGISTICS/CONSTRUCTION stage. The software used is called AHP-OS, which works as follows.

1. Which factor is more important to achieve effective supply chain management in panelised construction and how many more on a scale of 1 to 9?

Reflection and conclusion:

1. We are now at the end of the interview. Thank you!

2. Is there anything else you would like to add?

Appendix 3. Interview protocol supply chain expert from shipbuilding industry

Introduction

Hello, my name is Aaron. I am conducting this interview as part of a research study into the Critical Success Factors of effective supply chain management. The purpose of this interview is to gain insights into which success factors are crucial for the supply chain of panelised construction. All information you share will be anonymised. To give you a clearer understanding of the context of the research, which includes prefabricated construction and the concept of supply chain within this context, I have prepared a PowerPoint presentation.

General questions

1. Can you briefly introduce yourself and indicate which roles you have fulfilled, especially in the field of supply chain management and prefabrication?

A) To what extent are you familiar with prefab?

B) To what extent are you familiar with supply chain management?

2. What does the supply chain of the company you work look like?

3. Metadecor often acts as a subcontractor for the client, who is usually the main contractor. What about the company where you work and generally in the Yacht building sector?

4. And what about the integration of information and communication technologies? In the construction world, for example, BIM is a big concept and there are also technologies such as GIS.

5. And then a broadly interpretable question. What do you think of the construction sector?

6. Suppose you switch to the custom prefab construction sector, where supply chain management is still in its early stages. How would you implement effective supply chain management here?

Assessment of factor relevance

1. Are there any additional factors that you consider important for a company operating within the panelised construction supply chain, or do you consider this list complete?

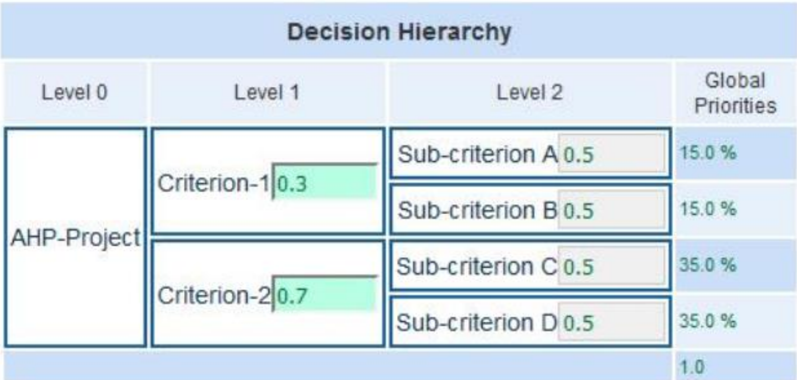
2. Do you think some success factors are not critical success factors for Metadecor's supply chain?

Appendix 4. Detailed explanation of CSFs ranking process AHP-OS

When the hierarchy was made final, the ranking could be done of the different CSFs of the 5 subcategories. This was done in the software AHP-OS. In this software the participants had to rank every CSFs per subcategory. To improve the understanding of the factors which had to be ranked the definitions of every CSF could be shown to enhance the ranking process. The panel had to conduct comparative judgements which is defined as making judgements about the relative importance of the elements with respect to the overall goal, which is the prioritisation of the CSFs of achieving effective supply chain management in panelised construction (Mu & Pereyra-Rojas, 2017).

In Figure 13, we observe a simple example of a two-level hierarchy. This graphic illustrates that at the first level, which represents the main criteria or subcategories in this research, predefined weights are assigned. 'Criterion-1' is assigned a weight of 30%, while 'Criterion-2' is assigned a weight of 70%. For the two sub-criteria, A and B, which are called factors in this research, the weights are set to the default value of $1/n_{leaf}$, where 'leaf' is the number of sub-criteria under the main criteria. This implies that both A and B are considered equally important. Consequently, both sub-criteria under 'Criterion-1' have a global priority of 15% (Goepel, 2018b). In this research the usage of predefined weights was not used, as the goal of the study is to achieve a ranked list of CSFs.

Figure 13. Illustration of a two-level decision hierarchy with four leaves.



Note. Reprinted from *Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS) by Klaus Goepel, 2018, International Journal of the Analytic Hierarchy Process 10, (p. 471)*

Before the comparisons began, participants were instructed that it was crucial to gain an overview of the entire supply chain. However, they were also reminded not to overlook their perspective on the collaboration between their specific stage in the supply chain and the overall supply chain of Metadecor. Additionally, they were informed of the stage they were categorised in, which could be design, production, logistics, or construction. With every pairwise comparison made the panellists were asked the question: ‘Which factor is more important in achieving effective supply chain management in panelised construction, and by how much more on a scale from 1 to 9?’

All of the judgements for the factors were first entered using the fundamental AHP scale shown in Table 1. The vector of priorities is the principal eigenvector of the matrix. This vector gives the relative priority of the factors measured on a ratio scale. When there is ensured that these priority vectors sum up to 1, these priorities are always unique (Saaty & Vargas, 2012). In Table 12 the input data of the subcategory ‘communication and collaboration’ of one of the experts can be seen with the priority vector. In this case there can be seen that CSF5 and CSF7 are seen as equally important. When CSF5 is compared to CSF9 there can be seen that CSF5 gets an extremely strongly preferred over CSF9 so a 9 is entered. The priority vector of CSF5 is with 0.291 the highest, so it can be seen as the most important factor to achieve effective supply chain management, in the subcategory ‘communication and collaboration’ according to this particular expert. The local priority vector is calculated using the power method by Larson et al (2013), which gives an accepted approximation

Table 12. Input data of expert on subcategory ‘Communication and collaboration’.

	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	Priority vector
CSF3	1	0.13	0.14	0.33	0.16	3	0.25	0.33	0.03
CSF4	8	1	1	1	1	8	3	2	0.167
CSF5	7	1	1	4	1	9	8	8	0.291
CSF6	3	1	0.25	1	1	8	7	5	0.169
CSF7	6	1	1	1	1	7	7	7	0.214
CSF8	0.33	0.13	0.11	0.13	0.14	1	0.17	0.14	0.016
CSF9	4	0.33	0.13	0.14	0.14	6	1	1	0.053
CSF10	3	0.5	0.13	0.2	0.14	7	1	1	0.056

Note. Own work

error of 1.E-7 (Goepel, 2018b). Based on this data the Consistency Ratio (C.R.) can be calculated which is 9.2%. Generally a C.R. of 10% or lower is considered acceptable, if the C.R. exceeds this threshold, it indicates a lack of judgemental consistency (Saaty & Vargas, 2012). This C.R. is calculated by the linear fit proposed by Alonso and Lamata (2006) where λ is R.I. and n is the number of criteria in the model:

$$\text{C.R.} = \frac{\lambda - n}{2.7699 \cdot n - 4.3513 - n}$$

Table 13 displays the pairwise comparisons of subcategories by the same participant. It is evident from the table that 'adaptability' is considered more important than other subcategories, with a priority vector of 0.313. Conversely, 'sustainability' is rated as the least important, with a priority vector of only 0.025.

Table 13. Input data of expert on comparison between subcategories.

	Forecast capacity	Communication and collaboration	Robustness	Adaptability	Sustainability	Priority vector
Forecast capacity	1	1	0.33	0.25	9	0.148
Communication and collaboration	1	1	1	1	9	0.229
Robustness	3	1	1	1	9	0.285
Adaptability	4	1	1	1	9	0.313
Sustainability	0.11	0.11	0.11	0.11	1	0.025

Note. Own work

Appendix 5. Detailed explanation calculation method used for ranking

AHP-OS takes usage of the weighted geometric mean aggregation of individual judgements to come up with the aggregated weights (Goepel, 2018b). Although there are multiple methods present for this calculation, the method could depend on the specific application (Grošelj et al., 2015; Wu & Chu, 2008). The weighted geometric mean aggregation of individual judgements is the only method that meets several required axiomatic conditions. To form the consolidated decision matrix a_{ij}^{cons}, AHP-OS calculates the geometric mean and standard deviation of all K participant's individual judgements pwc_k. The following equations are used in AHP-OS. The sum over K participants gets calculated as follows: $pwcx = \sum_{k=1}^{K} ln(pwck)$. This makes it possible to compute the geometric mean with $pwc_{CONS} = exp\left(\frac{pwcx}{K}\right)$. To form the consolidated decision matrix the data of the pairwise comparison data from the geometric mean is incorporated in the following equation: $a_{ij}^{cons} = exp\left(\prod_{k=1}^{K} a_{ij}\right)^{\frac{1}{K}}$. AHP-OS computes the standard deviation to estimate the weight variations based on the judgement variations. For this, the square sum over K participants is needed which can be calculated with the equation: $pwcx2 = \sum_{k=1}^{K} ln(pwck)]^2$. With this input the standard deviation can be calculated with: $pwc_{SD} = exp\left(\sqrt{\frac{pwcx2 - \frac{1}{K} pwcx \cdot pwcx}{K-1}}\right)$(Goepel, 2018b).

The weighted geometric mean gets calculated for every CSF resulting in a group result based on the judgements of all experts. AHP-OS also gives the geometric mean for every participant per CSF. This is calculated by multiplying the weight of the subcategories with the corresponding CSF (Goepel, 2018b). In order to combine the result of the expertise assessment with the results of the CSF hierarchy. The same approach as used in Zhang et al (2020) was adopted. In this paper the comprehensive weight of the indicators was based on the combination between the consistency degree of the judgement matrix which resulted in the amount of influence each expert was attained and the priority vectors of every factor scored by each of the experts. Here the normalised expert weight was multiplied by the weight of the criteria scored by the experts.

The following equation was used to combine the two AHP models in the research.

"$W_j = \sum_{i=1}^{n} K_i W_{ij} (i = 1,2,\cdots 10, j = 1,2,\cdots 6)$(Zhang et al., 2020)"

Where K_i is the normalised combined weight of the expert i. and W_{ij} was the weight of the expert I to the criteria j. In this research the same equation will be used with the corresponding 21 CSFs and the different weights of the 8 experts: $W_j = \sum_{i=1}^{n} K_i W_{ij} (i = 1,2,\cdots 8, j = 1,2,\cdots 21)$ (Zhang et al., 2020).

Appendix 6. Interview protocol current supply chain management level

Research question:

How can a complex façade system manufacturer using panelised construction achieve effective supply chain management?

Interview guide:

I will be recording the interview from now on. Do you have any questions before I do this?

1. What are typical panelised construction projects at Metadecor? Complex, very customer specific with a lot of engineering work.

2. Did the CSFs from this study have a major role in the previously mentioned projects? And in what way?

3. Do you think CSFs 1 to 8 played a greater role in the projects?

5. What do you think will happen if less attention is paid to the other CSFs?

6. Are there factors in this list that cannot be implemented until another factor is present?

7. The supply chain manager in shipbuilding stated that it is important for a company to know where it is in the Rozemeijer and Van Weele development model. Where do you think Metadecor is located? How mature is the company in terms of supply chain management? And why do you think this?

8. I had heard from other interviewees that you have moved away from a focus on only the lowest price.

9. Where do you think Metadecor could improve the most when looking at the purchasing development model?

10. Why do you think the top 8 CSFs are most highly rated by the experts in this supply chain?

11. Could it be related to the phase that metadecor is in?

12. Where could metadecor improve the most based on the model of the different supply chain phases? True "The supply chain includes all activities associated with the flow and transformation of goods from the raw material (extraction) stage, through to the end user, as well as the associated flow of information both up and down the supply chain" (Handfield & Nichols, 1999). And "Supply Chain Management (SCM) is the integration of these activities through improved supply chain relationships to achieve a sustainable competitive advantage" (Handfield & Nichols, 1999).

13. How could these CSFs contribute to taking Metadecor to the next stage in the model?

14. And how could that be done?

Generalisability

1. How different are Metadecor's projects compared to each other?

2. Do you think these CSFs depend on the type of project, and that their prioritisation of importance might differ between traditional projects?

3. How different are Metadecor's projects compared to other projects from competitors or other companies using panelised construction?

We are now at the end of the interview. Thank you!

Appendix 7. References from literature for CSFs of off-site construction ranking

Table 14. Table 3. References from literature for CSFs in off-site construction.

NO	SUCCESS FACTOR NAME	REFERENCES
CSF1	Extensive project planning	Luo *et al.* (2020) Arshad & Zayed (2022) Wuni & Shen (2022) Wuni *et al.* (2020) Wuni & Shen (2020b) Hussein & Zayed (2021) Wuni & Shen (2020a)
CSF2	Risk management	Arshad & Zayed (2022) Bevilacqua *et al* (2018) Wuni *et al.* (2020) Hussein & Zayed (2021) Aloini *et al.* (2012) Lu *et al.* (2022) Zhang *et al.* (2023) Liu & Liu (2023) Wuni & Shen (2020b)
CSF3	Information sharing	Zhang & Li (2023) Wuni & Shen (2020b) Cano *et al.* (2015) Wuni & Shen (2020a) Zhang & Ji (2021) Zhang *et al.* (2023) Bevilacqua *et al.* (2018) Aloini *et al.* (2012) Zhao *et al*. (2022) Lönngren *et al.* (2010)
CSF4	Effective use of information and communication technology	Wuni *et al.* (2020) Liu & Liu (2023) Aloini *et al.* (2012) Zhang *et al.* (2021) Wuni & Shen (2020b) Zhang *et al.* (2023) Lu *et al.* (2022)
CSF5	Early involvement of critical stakeholders	Wuni & Shen (2020b) Aloini *et al.* (2012) Wuni *et al.* (2020)
CSF6	Active involvement of key participants throughout the project	Wuni & Shen (2020b) Wuni *et al.* (2020) Wuni & Shen (2020a)
CSF7	Coordination of offsite and onsite work packages	Vrijhoef (2000) Wuni & Shen (2020a) Wuni & Shen (2020b) Wuni *et al.* (2020) Zhao *et al*. (2022)

		Cano *et al.* (2015) Zhang *et al.* (2023) Arshad & Zayed (2022) Luo *et al.* (2020) Wuni & Shen (2022) Wuni & Shen (2023) Aloini *et al.* (2012) Lönngren *et al.* (2010)
CSF8	Avoidance of dysfunctional conflicts	Wuni & Shen (2023) Wuni & Shen (2020b) Aloini *et al.* (2012)
CSF9	Closer relationship with partners with collaboration	Bevilacqua *et al.* (2018) Zhang *et al.* (2021) Riazi *et al.* (2019) Zhang *et al.* (2023) Cano *et al.* (2015) Wuni *et al.* (2020) Lönngren *et al.* (2010)
CSF10	Creating long-term partnerships with trust	Vrijhoef (2000) Lönngren *et al.* (2010)
CSF11	Adequate knowledge and good contractor leadership	Zhao *et al*. (2022) Wuni & Shen (2020b) Luo *et al.* (2020) Wuni & Shen (2020a)
CSF12	Selecting competent and experienced key players	Wuni & Shen (2023) Aloini *et al.* (2012) Zhao *et al*. (2022)
CSF13	Standardised factory-made components	Zhao (2021) Aloini *et al.* (2012) Zhao *et al*. (2022)
CSF14	Quality assurance and quality control	Zhao (2021) Cano *et al.* (2015) Wuni & Shen (2020a) Zhang *et al.* (2023)
CSF15	Inventory management and control	Wuni & Shen (2022) Zhang *et al.* (2023) Liu & Liu (2023) Vrijhoef (2000)
CSF16	Low supply chain response time	Zhang *et al.* (2023) Zhao *et al*. (2022) Liu & Liu (2023)
CSF17	High logistics support level	Lu *et al.* (2022) O'Connor et al. (2014) Zhao *et al*. (2022) Wuni & Shen (2020a) Wuni *et al.* (2019) Zhang *et al.* (2023) Wuni & Shen (2022)
CSF18	High manufacturing capability	Wuni & Shen (2020a) Zhao (2021)
CSF19	Multi-component manufacturer supply	Zhang *et al.* (2021) Zhang *et al.* (2023) Arashpour et al. (2017)
CSF20	Integrating principles of the circular economy in the supply chain	Wuni & Shen (2022)
CSF21	Promoting sustainability	Arshad & Zayed (2022)

Note. Own work

Appendix 8. Comparison of expertise and no expertise percentage ranking

Table 15. Factor weightings comparison with expertise weighting difference vs. without expertise weighting difference.

Ranking with expertise weighting			
Factors	**Percentage**	**Ranking**	**Cumulative percentage**
Low supply chain response time **(CSF16)**	11,43%	1	11,43%
Active involvement of key participants throughout project **(CSF6)**	10,59%	2	22,01%
Robust design **(CSF15)**	9,10%	3	31,11%
Multi-component manufacturer supply **(CSF19)**	8,82%	4	39,93%
High logistics support level **(CSF17)**	8,78%	5	48,71%
Early involvement of critical stakeholders **(CSF5)**	6,18%	6	54,89%
Coordination of offsite and onsite work packages **(CSF7)**	5,56%	7	60,45%
Adequate knowledge and good contractor leadership **(CSF11)**	5,40%	8	65,85%
Integrating circular economy principles into the supply chain **(CSF20)**	4,97%	9	70,82%
Effective use of information and communication technology **(CSF4)**	4,25%	10	75,07%
Risk management **(CSF2)**	3,79%	11	78,85%
Selecting competent and experienced key players **(CSF12)**	3,30%	12	82,16%
Creating long-term partnerships with trust **(CSF10)**	3,05%	13	85,20%
Closer Relationship with partners with collaboration **(CSF9)**	2,41%	14	87,62%
High manufacturing capability **(CSF18)**	2,27%	15	89,89%
Information sharing **(CSF3)**	2,19%	16	92,09%
Extensive project planning **(CSF1)**	2,18%	17	94,27%
Quality assurance and quality control **(CSF14)**	2,02%	18	96,29%
Standardized factory-made components **(CSF13)**	1,77%	19	98,06%
Avoidance of dysfunctional conflicts **(CSF8)**	1,21%	20	99,27%
Promoting sustainability **(CSF21)**	0,73%	21	100,00%

Ranking without expertise weighting			
Factors	**Percentage**	**Ranking**	**Cumulative percentage**
High logistics support level **(CSF17)**	10,78%	1	10,78%
Low supply chain response time **(CSF16)**	8,72%	2	19,50%
Adequate knowledge and good contractor leadership **(CSF11)**	6,73%	3	26,23%
Multi-component manufacturer supply **(CSF19)**	6,46%	4	32,70%
Selecting competent and experienced key players **(CSF12)**	5,69%	5	38,39%
Effective use of information and communication technology **(CS**	5,61%	6	44,00%
Extensive project planning **(CSF1)**	5,24%	7	49,23%
Active involvement of key participants throughout project **(CSF**	4,97%	8	54,21%
Risk management **(CSF2)**	4,94%	9	59,15%
Early involvement of critical stakeholders **(CSF5)**	4,75%	10	63,89%
Coordination of offsite and onsite work packages **(CSF7)**	4,58%	11	68,48%
Creating long-term partnerships with trust **(CSF10)**	4,39%	12	72,87%
Integrating circular economy principles into the supply chain **(C**	4,18%	13	77,05%
Closer Relationship with partners with collaboration **(CSF9)**	4,03%	14	81,08%
Robust design **(CSF15)**	3,92%	15	85,00%
High manufacturing capability **(CSF18)**	3,54%	16	88,54%
Promoting sustainability **(CSF21)**	2,95%	17	91,48%
Quality assurance and quality control **(CSF14)**	2,70%	18	94,18%
Standardized factory-made components **(CSF13)**	1,99%	19	96,17%
Information sharing **(CSF3)**	1,97%	20	98,14%
Avoidance of dysfunctional conflicts **(CSF8)**	1,87%	21	100,00%

Note. Own work

Appendix 9. Comparison of clustered and non-clustered percentage ranking

Table 16. Factor weightings comparison without expertise weighting difference, no cluster without vs. clustered without.

No cluster without expertise difference			
Factors	**Percentage**	**Ranking**	**cumulative percentage**
High logistics support level	10,78%	1	10,78%
Low supply chain response time	8,72%	2	19,50%
Adequate knowledge and good contractor leadership	6,73%	3	26,23%
Multi-component manufacturer supply	6,46%	4	32,70%
Selecting competent and experienced key players	5,69%	5	38,39%
Effective use of information and communication technology	5,61%	6	44,00%
Extensive project planning	5,24%	7	49,23%
Active involvement of key participants throughout the project	4,97%	8	54,21%
Risk management	4,94%	9	59,15%
Early involvement of critical stakeholders	4,75%	10	63,89%
Coordination of offsite and onsite work packages	4,58%	11	68,48%
Creating long-term partnerships with trust	4,39%	12	72,87%
Integrating circular economy principles into the supply chain	4,18%	13	77,05%
Closer Relationship with partners with collaboration	4,03%	14	81,08%
Robust design	3,92%	15	85,00%
High manufacturing capability	3,54%	16	88,54%
Promoting sustainability	2,95%	17	91,48%
Quality assurance and quality control	2,70%	18	94,18%
Standardized factory-made components	1,99%	19	96,17%
Information sharing	1,97%	20	98,14%
Avoidance of dysfunctional conflicts	1,87%	21	100,00%

Clustered without expertise difference			
Factors	**Percentage**	**Ranking**	**cumulative percentage**
High logistics support level	10,10%	1	10,10%
Multi-component manufacturer supply	7,45%	2	17,54%
Low supply chain response time	7,44%	3	24,98%
Effective use of information and communication technology	7,19%	4	32,18%
Risk management	6,27%	5	38,44%
Adequate knowledge and good contractor leadership	6,18%	6	44,62%
Coordination of offsite and onsite work packages	6,04%	7	50,65%
Selecting competent and experienced key players	5,88%	8	56,54%
Extensive project planning	5,66%	9	62,19%
Active involvement of key participants throughout the project	5,41%	10	67,60%
Early involvement of critical stakeholders	5,15%	11	72,75%
Robust design	4,87%	12	77,61%
Creating long-term partnerships with trust	4,64%	13	82,25%
Closer Relationship with partners with collaboration	4,25%	14	86,50%
Quality assurance and quality control	2,92%	15	89,42%
High manufacturing capability	2,88%	16	92,30%
Integrating circular economy principles into the supply chain	1,98%	17	94,27%
Standardized factory-made components	1,90%	18	96,18%
Promoting sustainability	1,71%	19	97,89%
Information sharing	1,18%	20	99,07%
Avoidance of dysfunctional conflicts	0,93%	21	100,00%

Note. Own work