Research Article

Towards Safer and More Efficient Logistics: Rack Specifications for Prefabricated Façade Panels

Moslem Sheikhkhoshkar[1], Mahmoud Karaz[2], Hind Bril El Haouzi[3]

1 Lecturer in Digital Construction, University of Greenwich, London, UK, m.sheikhkhoshkar@greenwich.ac.uk
2 Post-Doctoral Fellow in CRAN, University of Lorraine, Nancy, France, mahmoud.karaz@univ-lorraine.fr
3 Full Professor in CRAN, University of Lorraine, Nancy, France, hind.el-haouzi@univ-lorraine.fr
Correspondence: m.sheikhkhoshkar@greenwich.ac.uk

Abstract

The increased use of modular construction focuses on streamlined rack systems, but the existing ad-hoc-based plans for stacking logistics require a methodical approach. This paper provides a comprehensive guideline on rack specification to support the safe, efficient, and cost-effective transportation of prefabricated façade panels during modular integrated construction (MiC), addressing issues such as instability and damage in transit. A mixed-methods design combines a five-step process, which involves a literature review and existing standards (e.g., EN 12195; ISO 1496-1), a two-round Delphi questionnaire, 13 specialists, statistical analysis, and a validation rack design of an industrial supplier against the developed specifications. The most significant results include seven drivers, such as Panel Characteristics, Handling/Loading-Unloading, Transportation Conditions, Cost and Budget, Safety and Stability, Modularity and Adaptability, and Space Efficiency, each with 25 factors, and safety and stability (e.g., vibration resistance, mean 4.538, SD 0.877) are the top drivers. The novel specification guide fills industrial design gaps, such as poor fastening mechanisms. These are small sample sizes and untested second-round data, suggesting that further validation is needed. In practice, the guide supports architecture and construction logistics by delivering panels free of damage, and the partner's design ensures compliance with trailer compatibility. However, fasteners need to be improved to guarantee a higher level of safety. It also fosters sustainable urban development by reducing costs and delays, as well as offering potential benefits to society, such as improved living conditions resulting from efficient renovations.

Keywords: rack specification; façade panels; modular construction; design for logistics; safety standards

Highlights

- Develops a rack specification guide for safer, efficient façade panel transport.
- Highlights safety and stability as critical drivers, with a secure fastening key.
- Notes cost less, prioritising performance over short-term savings.

1 Introduction

The growing interest in modular integrated construction (MiC) and prefabrication has increased the necessity to mass-produce façade panels, as they are easily assembled, eliminate the risk of labour, and reduce costs compared to an on-site assembly (Montali et al. 2018; Rammig et al. 2023), and enable renovation on existing buildings (Seghezzia and Masera 2015). However, transporting these large and heavy panels is associated with several challenges, such as the stability during the transportation process, the compliance with the design requirements, and the logistics optimisation, which is compromised by the ad-hoc stacking plans instead of scientific approaches, exposing this mode of transportation to the possibility of instability of the panels and damage (Wang et al. 2023). The specifications of rack systems are a critical solution for ensuring the safety of these systems, optimising logistics efficiency, and reducing unnecessary costs associated with façade panel logistics. (Miklautsch and Woschank 2023; Wang et al. 2023), and custom designs are improving logistics (Karaz and Teixeira 2023). Proper planning and comprehensive rack specifications are crucial to resolving such transportation issues.

Rack systems are designed to counter technical requirements, logistical limitations, economic viability, and safety provisions, eliminating damage and ensuring smooth transportation of the façade panels (Wehrli 2003). Although logistics of modular constructions have improved, the area of the integration of multidimensional findings into the rack system, including structural health monitoring, a buffer mechanism, and transport timeline, remains a knowledge gap (Arshad and Zayed 2024; Wang et al. 2023). Racks designs can be driven by two competing factors, cost and technical factors versus safety compliance. The former emphasises focusing on purchasing and operational costs, as well as the geometrical characteristics of the façade panels and transportation containers. The latter focuses on the mechanical design, including the use of connectors, protections, buffers, and dampers. (Gehring and Rüppel 2023; Yusof, Nawi, and Jabar 2023; Zelinska, Boldyrieva, and Amelina 2018). The adverse effects of gaps between these factors consist of exposure to a greater possibility of the panel being damaged, slow delivery in the supply chain, and elevated costs (Abeysinghe, Waidyasekara, and Melagoda 2018).

Transporting façade panels safely, efficiently, and cost-effectively is critical to prefabrication projects. Given the panelized nature of the renovation approach, racks play a crucial role in ensuring damage-free delivery from the off-site manufacturing facility to the construction site. Selecting suitable racks requires thoughtful consideration of multiple technical and contextual factors, which vary based on the physical characteristics of the panels, logistics constraints, handling practices, and the needs of stakeholders. The process of rack selection is complex and not straightforward due to four challenges. (1) variability in panel types in terms of differences in size, weight, and materials, which lead to handling requirements. (2) logistics considerations related to the mode of transport, handling equipment, loading and unloading methods, and site constraints. (3) Stakeholder requirements lie in preferences and constraints from logistics planners, site managers, and factory engineers. (4) Contextual constraints are identified as being linked to regulations and environmental and safety factors at the production and installation locations. The complexity of issues requires an iterative, holistic technique to define the chosen rack. The process is complemented with metrics referred to as control metrics, where workflow reliability and constraint management are achieved via rack performance monitoring to enable timely and damage-free deliveries (Sheikhkhoshkar et al., 2024).

To address the identified research and practical gaps, this paper provides a structured approach for identifying rack requirements based on project-specific drivers. It supports internal decision-making and communications with external suppliers, ensuring functional needs and expectations are aligned. The paper sections are organised as follows: the subsequent section reviews the extant literature, standards and guidelines to extract the rack design core drivers and their factors, the third section justifies the research methodology used in this paper, the fourth section shares the key findings in terms of thematic analysis result, data preprocessing, statistical analysis, and rating system for the rack design variables. The discussion section discusses the critical rack design specifications and validates the compliance of the rack design supplied by the industrial partner. The final section concludes the research findings, identifies key limitations and lists a future research agenda.

2 Literature Review

This section outlines the key variables involved in the rack system for transporting panels to the facade, with a specific focus on technical, logistical, economic, and safety factors (Arshad & Zayed, 2024; Wehrli, 2003). The designer's decision-making processes for specifying rack design parameters should employ an evidence-based method to enhance rack design and operations, thereby minimising facade panel damage across the supply chain (Zhang et al., 2024).

The technical factors during designing for racks focus on allocating buffers, dampers, and monitoring sensors (Wang et al. 2023), and real-time monitoring to reduce the risks throughout the transit (Brandín and Abrishami 2024). Efficiency and reliability in transportation are essential components of logistics. Previous studies have explored various approaches to achieve this, including the integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) (Niu, Yang, and Pan 2019), as well as the use of vehicle routing algorithms and multi-agent simulations (Attajer and Mecheri 2024). These methods aim to optimise scheduling and routing to support Just-in-Time (JIT) delivery. These techniques address the density and location limitations of urban settings but require additional confirmation in various geographic and regulatory contexts. Economic factors involving cost-efficient planning and environmentally friendly transportation (Miklautsch, Woschank, and Heißenberger 2024; H. Wang et al., 2024). Nevertheless, designers tend to prioritise short-term expenditures over life-cycle analysis, suggesting that more comprehensive sustainability studies should be conducted. It is essential to evaluate its safety and compliance with the industrial standards and guidelines, where designs include torsion and vibration absorption mechanisms (Bouwkamp, Dexter, and Rumsey 2007), and automatic verification systems (Saeed et al., 2024), but interoperability remains a problem. This paper addresses these gaps by developing a novel specification of rack design for modular façade panels that drives the design towards safe and efficient logistics.

3 Research Methodology

This paper applies a mixed-methods study with a five-stage framework to rigorously develop a rack specification for transporting prefabricated panels (see Figure 1). The qualitative and quantitative methods are combined to avoid gaps in collecting the required information and ensure a comprehensive, evidence-based development process for guidelines (Creswell & Creswell, 2018). The first stage involves a literature review that covers state-of-the-art academic sources, industry regulations, and policies related to construction logistics, handling in prefabrication, transportation safety, and prefabrication. The relevant literature was retrieved from peer-reviewed journals concerning major topics, including panel handling of façades, transport rack engineering, and modular transportation systems. Industry standards, which included EN-12195, ISO-1496-1, ISO-1161, ISO-3874 and BS-EN-12642 (Code XL), were critically analysed to align with regulatory and practical requirements. This stage aims to identify and synthesise a comprehensive list of underlying drivers (primary criteria that impact rack selection) and their associated factors (extensive sub-criteria) derived from the studied sources. The result of this stage is a synthesised list of drivers and factors, which the expert consultation will be based on, and is built as a source of further specialist consultation.

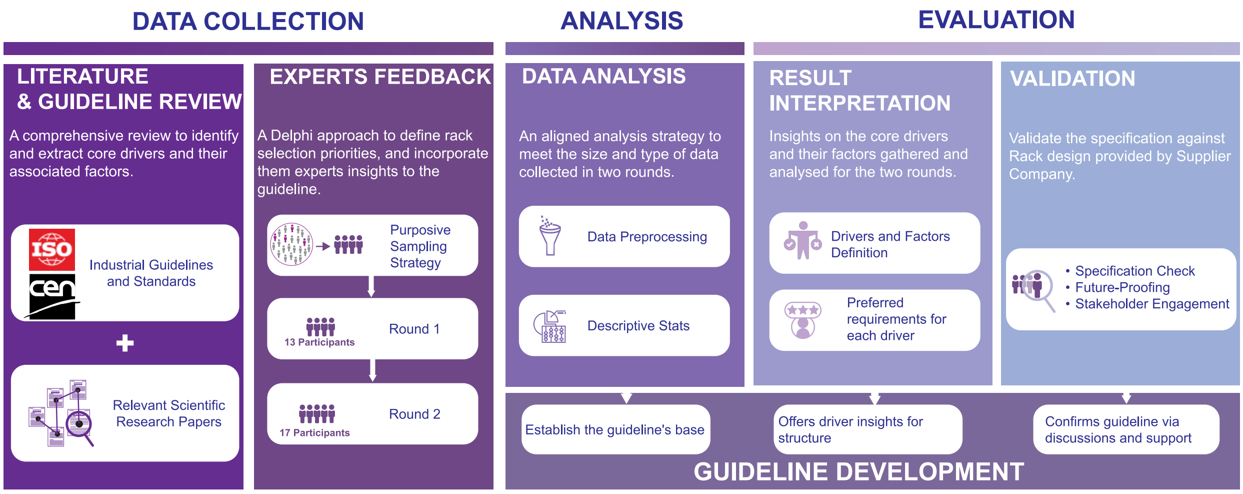


Figure 1. Research methodology followed in this paper

In the second stage, this study employs purposive sampling to choose participants with specialised knowledge of construction logistics, transportation, and rack engineering (Patton 2015; Sheikhkhoshkar et al. 2025). The purposive sampling procedure prioritises experienced individuals in construction logistics, transportation, and rack engineering. In particular, the participant groups consist of four cohorts: (1) construction managers and site managers; (2) logistics managers, logistics planners, and specialists; (3) transportation suppliers and truck drivers; and (4) rack providers and suppliers.

The second stage focuses on gathering expert feedback with a structured process. In the first round, the factors identified from the literature and guidelines were first presented, and specialist feedback was sought to refine the drivers and factors. In the second round, 13 stakeholders involved in the project, including construction managers, logistics specialists, transportation experts, and rack suppliers, were surveyed to assess the perceived importance of these drivers and factors for rack selection. The third stage involves analysing round 2 data from 13 participants using descriptive statistics (averages, standard deviations) for factor importance rankings, clustering, outlier detection, and correction. In the fourth stage, the insights are interpreted to create a thorough rack specification guide. The guide organises key drivers, tier classifications, factor definitions, least and most desired requirements, and recommendations to align supplier offerings with project logistics. It serves as a briefing document for logistics firms and rack manufacturers, as well as an internal tool for defining project requirements and ensuring operational readiness.

4 Key Findings

4.1 Key drivers and their factors

The result of a comprehensive literature review and the first round of Delphi expert consultations are mapped in Figure 2. It lists seven key drivers and twenty-five related factors. This illustration presents a thematic framework for identifying the critical decision drivers in rack selection. It depicts them as operational, economic and adaptive considerations in industrial logistics and transportation scenarios.

At its core are the "Decision Drivers of Rack Selections," which are delineated into seven major drivers (D1-D7) with twenty-five factors (F1-F25) specified as related to rack design, procurement, manufacturing, stacking process, transportation, storage, and installation.

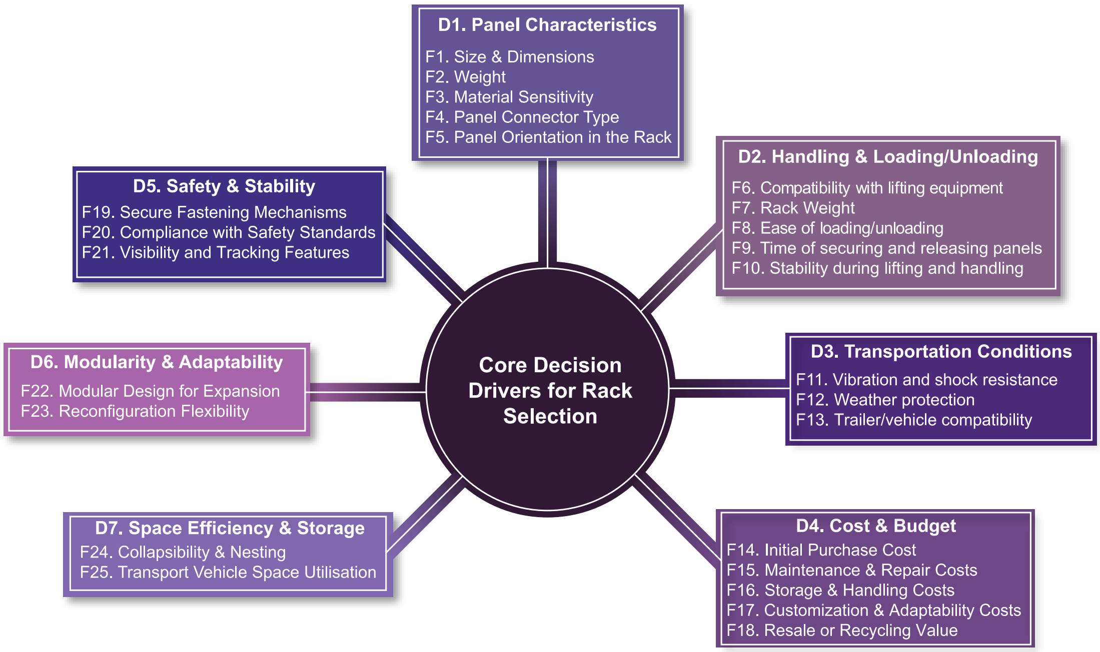


Figure 2. Thematic analysis of the core decision drivers for rack selection and their related factors

Driver D1, Panel Characteristics, includes size and dimensions (F1), affect the overall length, width, and thickness of the façade panel, which would impact rack compatibility; weight (F2) to define the total load capacity and structural needs; material sensitivity/type (F3) to address the fragility of the materials utilised in the panels and susceptibility to cracking; panel connector type (F4) to address how facade panels' connectors can be adjusted into the racks without causing instability.; and panel orientation within the rack (F5) to define the space efficiency based on vertical or horizontal orientation of panel. D2, Handling and Loading/Unloading, is relevant to compatibility with lifting equipment, which can affect transporting efficiency, handling, and lifting; the ease of loading/unloading the rack on to transport vehicles (F8), which can increase the speed of operations; the ease of securing and releasing meat panels to the rack (F9), and the stability of the rack during lifting and handling (F10) which can contribute to maintaining stable workflows during lifting or transporting the racks. Transportation Conditions (D3) include vibration and shock resistance (F11), which is essential to avoid any damage to any panel during transit; weather protection (F12), protecting against rain, moisture, and extreme temperatures via the use of covers or devices; and trailer/ vehicle compatibility (F13), providing compatibility with various transport vehicles used to transport racks. Cost and Budget (D4) involves five factors: the cost of initial purchase (F14), as it is the upfront cost of acquiring the rack; (F15) the maintenance and repair costs for the rack; the storage and handling costs (F16), which represents the related expenses of storing and handling of empty racks; the customisation and adaptability costs (F17), the modification costs of racks for different panel types; and the resale or recycling values (F18), entails potential savings from repurposing or reselling racks.

The category of Safety and Stability (D5) highlights the necessity of risk mitigation, with the focus on safe fastening systems (F19) that promote the secure anchoring of panels to avoid shifting or damage when transporting; the safety criteria (F20), which ensures that the transportation of the façade panels does not violate established regulations and requirements of the industry; and visibility and tracking (F21), which confirms the importance of transparent and monitoring racks when transported to ensure ultimate safety and protection. Adaptability and Modularity (D6) emphasises the importance of future flexibility, such as modular design to expand (F22), which facilitates the ease of adding or removing components to accommodate changing transport requirements. Additionally, it highlights flexibility to reconfigure (F23), enabling modifications to the rack to support different panel sizes. Finally, Space Efficiency and Storage (D7) deals with the urgency of space optimisation, collapsibility and nesting (F24), which implies the ability of racks for folding or nesting to save space when unloaded; and transport vehicle space utilisation (F25), how well racks utilise the space available in trucks or transport containers. This simplistic summary asserts that an all-inclusive evaluation can be practical when adopting racking, considering the operational economies, compliance with relevant regulations, cost-effectiveness, and sustainability of long-term façade transport and handling processes.

4.2 Statistical Overview

Before conducting the statistical analysis, the researchers preprocessed the data collected in the survey to identify and address anomalies, ensuring consistency. Individuals with some outlier values were substituted using logical estimation, and others were flagged for validation. The small sample size justified the use of descriptive statistics: the mean values were utilised to ascertain central importance, and the standard deviation indicated either agreement or disparity among the respondents. The results of this study are informative, yet specific disparities are apparent, with greater standard deviations in certain factors, such as Connector Type (1.49) and Weight (1.18). This is why additional interviews with stakeholders are proposed in Round 2 (future work). Table 1 presents the statistical breakdown of survey respondents (N = 13), who clearly explained their priorities regarding rack selection. Table 2 shows a tier structure as a classification approach that can inform decisions regarding rack selection, based on expert surveys. It categorises factors into; Tier 1 (Critical: mean of responses equals 4.5 or above and a standard deviation of 0.7 or less, signifying factors of exceptional importance that everyone agrees are extreme, vast significance), Tier 2 (Important: mean of responses equals 3.5- less than 4.5 or 4.5 and standard deviation of more than 0.7, which denotes location specific significance), and Tier 3 (Context-This framework integrates statistical measures with expert opinions in prioritising drivers).

Table 1. Descriptive statistical analysis for the rack selection specification's drivers and factors

Core Decision Drivers and Detailed Factors for Rack Selection	Average of Importance	Standard Deviation	Tier Classification
D.1. Panel Characteristics	**4.308**	**0.751**	**Tier 2**
F.1. Size & Dimensions	4.231	0.832	Tier 2
F.2. Weight	3.308	1.182	Tier 3
F.3.Material Sensitivity	4.462	0.776	Tier 3
F.4. Panel Connector Type	3.692	1.494	Tier 2
F.5. Panel Orientation in the Rack	3.692	0.947	Tier 2
D.2. Handling & Loading/Unloading	**4.538**	**0.519**	**Tier 1**
F.6. Compatibility with lifting equipment (e.g., cranes, forklifts)	4.385	0.506	Tier 2
F.7. Rack Weight	2.385	0.870	Tier 3
F.8. Ease of loading/unloading the rack onto transport vehicles	3.923	0.862	Tier 2
F.9. Time efficiency of securing and releasing façade panels from the rack	4.385	0.870	Tier 2
F.10. Stability of the rack during lifting and handling	3.923	1.256	Tier 2
D.3. Transportation Conditions	**4.462**	**0.519**	**Tier 1**

F.11. Vibration and Shock Resistance	4.538	0.877	Tier 2
F.12. Weather Protection	3.923	1.754	Tier 2
F.13. Trailer/Vehicle Compatibility	4.000	0.913	Tier 2
D.4. Cost & Budget	**2.692**	**1.316**	**Tier 3**
F.14. Initial Purchase Cost	2.231	1.013	Tier 3
F.15. Maintenance & Repair Costs	2.462	1.050	Tier 3
F.16. Storage & Handling Costs	2.846	0.987	Tier 3
F.17. Customisation & Adaptability Costs	3.462	0.967	Tier 3
F.18. Resale or Recycling Value	2.308	1.032	Tier 3
D.5. Safety & Stability	**4.692**	**0.480**	**Tier 1**
F.19. Secure Fastening Mechanisms	4.538	0.519	Tier 1
F.20. Compliance with Safety Standards	4.385	0.961	Tier 2
F.21. Visibility and Tracking Features	3.308	0.480	Tier 3
D.6. Modularity & Adaptability	**3.923**	**0.862**	**Tier 2**
F.22. Modular Design for Expansion	3.308	0.751	Tier 3
F.23. Reconfiguration Flexibility	4.154	0.899	Tier 2
D.7. Space Efficiency & Storage	**3.846**	**0.801**	**Tier 2**
F.24. Collapsibility & Nesting	3.462	0.967	Tier 3
F.25. Transport Vehicle Space Utilisation	3.923	1.038	Tier 2

Table 2. Tier's criteria system and rationale of each tier.

Tier	Criteria	Rationale
Tier 1 (Critical)	Mean ≥ 4.5 and SD* ≤ 0.7	Factors demonstrating high relevance and strong consensus among experts can be characterised as non-negotiable and essential design elements, on which the experts would strongly agree regarding their importance.
Tier 2 (Important)	Mean between 3.5 and 4.4, or mean ≥ 4.5 with SD > 0.7	Factors are also important, but can be context-specific or may have moderate agreement, allowing them to be powerful yet not universally dominant.
Tier 3 (Context-Dependent)	Mean < 3.5 or SD > 1.0	Most experts do not prioritise factors or show excessive variability in opinions, rendering them suitable only for project-specific considerations rather than standardisation.

* SD: Standard Deviation

The survey of project partners (N = 13) revealed essential factors that influenced the choice of racks for transporting fragile facade panels. Tier 1 drivers, based on average importance ratings, are D.2. Handling/Loading/Unloading, D.3. Transportation Conditions (average rating: 4.462), and D.5. Safety and Stability (average rating: 4.692). These highlight safety, risk reduction, and operational efficiency. D.5. Underlines the use of a secure fastening system (F.19) to prevent load movement during transit or installation, which may lead to risks of unstable operations in all parts of the stationary operation, transit operation, and raising operation. Operational effectiveness and workplace safety rely on compliance with safety regulations (F.20) and minimising the systemic risks in the supply chains and installations. D.2 highlights operational usability and is marked as a vital driver to ensure that the lifting equipment, including cranes and forklifts, is compatible with the design of panels. F.9 Efficient panel handling and simplified loading/unloading enhance productivity and minimise manual interventions that reduce the risk of mishandling. High stability in the lifting process will encourage ergonomic and sway-free systems that integrate smoothly in logistics. D.3. Transportation Conditions examines the challenges of long or complex routes and paths. The eleventh factor, Vibration and shock resistance (F.11), is needed to protect panels' structural and aesthetic integrity against transit stresses and torsion. Shock absorption mechanisms should be applied as an element of damping and reinforcement, focusing on material integrity rather than vehicle compatibility. Tier 3 (Cost and Budget D.4., Avg. 2.69) implied that participants prefer cost over functionality, durability, and safety in selecting the characteristics of panels and their racks. This observation indicates that stakeholders prioritise not short-term economic benefits, but rather performance. The essential requirements of rack design are included in the Tier 1 drivers. Solutions that fail to satisfy these criteria cannot be expected to fulfil the project's needs. The results highlight the importance of installing racks with robust fastening systems. The survey highlights the importance of stability, a secure fastening system, and transport resilience in ensuring safety and efficiency when dealing with delicate facade panels.

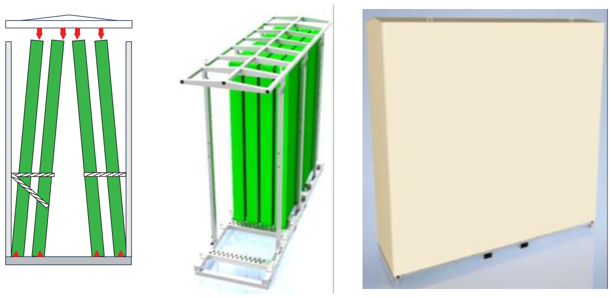
5 Rack Specification Guideline

The required specifications of racks needed to transport a façade panel in the context of the ByWall project were formulated and listed by analysis of parameters that were of the highest priority, as identified by the stakeholder consensus, taking into consideration non-negotiable parameters that ensured maximum safety, logistical ease of operations, as well as a seamless and well-integrated system. These specifications are to be incorporated into any viable rack design to make it feasible. (Attajer and Mecheri 2024). Racks should have secure fastening mechanisms to ensure locking arms or clamps (i.e., industrial-grade adjustable locking arms or clamps) and uphold tool-free connections to be easy and quick, but safe (Gehring and Rüppel 2023). Moreover, all panel connectivity points must evenly share loads using high-friction, non-abrasive contacts, such as rubber lining or silicone padding, to avoid scratches or micro-damage. Additionally, secondary securing options, such as mechanical clamps with tension straps, should be used to enhance transport stability. Satisfying the safety specifications is a must, and includes compliance with EU and ISO standards, including ISO-1161 (ISO, 2016) in corner fittings and EN-12195 (CEN, 2010) in loading restraint, along with edge/corner protective through padded frames of moulded insertions. Also, racks should have at least 75% lateral resistance/protective measures for each panel to reduce the risk of tipping or oscillations during dynamic situations.

Lifting and loading/unloading, including compatibility with lift equipment, requires the reinforcement of forklift pockets according to European pallet dimensions (CEN, 2010), including a full pallet weight, or top-mounted crane lifting eyes with certified crane hooks that can support 1.5 times their rated load to ensure a balanced lift, tested to a full weight and certified. Effectiveness in facilitating entry and removal of façade panels requires fast mounting mechanisms that allow operation within a minute per panel without requiring tools, ease of operator access that does not require crouching and consideration of clear labelling to promote usability. Proper lifting and handling stability, combined with a low centre of gravity design, reduces the tilt or swaying of a rack. The anti-tip base structure is especially effective when the rack is partially loaded or on rough surfaces. Easy loading/unloading onto transport vehicles is expected to occur with standard base dimensions consistent with standard trailer beds. Anti-slippery skids or lock-in channels are also available, and guided positioning with corner guides or centring rails minimises alignment and positioning errors. Transportation conditions specifications focus on eliminating vibrational and shock loads by incorporating built-in damping systems, such as rubber feet or cushioned panel seats, to absorb road-induced vibrations. A secure method of internal separation is also employed, creating a 10-20 mm spacing between panels with vibration-absorbing spacers that prevent direct contact between panels. Trailer/vehicle compatibility: a cross-vehicle profile adjustable to flatbed and closed European truck designs, with standard anchor points at all four corners to interface with ratchet straps and securely fasten (BSI 2017; ISO 2013). Weather resistance is achieved through corrosion-resistant treatments, such as hot-dip galvanisation or industrial powder coating, which resist rain, snow, and UV radiation. Weatherproof tarps or modular enclosures are available to protect against moisture and dust. Designing drainage holes and ventilation arrangements complements weatherproof traps to prevent water pooling during outdoor storage. An integrated connector accommodation mechanism is essential, featuring precision-fitting slots, notches, or adjustable holders that easily accommodate pre-installed panel connectors —such as hooks, rails, or bolts — with no need for additional tools or repositioning. This design should not be invasive or time-sensitive. However, it should maintain the on-site teams' handling efficiency and safety, as shock-absorbing paddings or locking brackets to connector housings can prevent loss or damage through accidental engagement.

5.1 Design and Validation of Racks for Supplier Compliance

This section validates the compliance of the rack design proposed by the industrial partner (see Figure 3) against the developed specification in this paper, while the specification served as a foundation for the rack design supplied by the design team. The main objective of this validation process is to address the transportation and handling of the façade panels.



(a) (b) (c)

Figure 3 - Rack design received from the racks supplier: (a) cross-sectional view showing the panel layout within the rack, (b) isometric view of the interior rack design with panels in green, (c) isometric view of the exterior rack design with cover.

Table 3 is grounded on an in-depth analysis to measure the compliance of technical and safety requirements for the supplier's proposed design (shown in Figure 4) with the rack design specification provided in this paper. The analysed drivers include D.5. Safety & Stability, D.2. Handling & Loading/Unloading, D.3. Transportation Conditions, and D.1. Panel Characteristics, to steer the rack design towards operational, ergonomic, and safe standards for handling and transporting prefabricated façade panels without incurring damage. Regarding D.5, the secure fast-centring mechanisms have not been sufficiently addressed because there is no information on locking arms or clamps. Using a preceding tension strap system can obstruct the stability of inclined panels. The supplier should clarify these factors and consider a different fastening system. Additionally, non-compliance with safety standards implies an additional input from suppliers, as the material will not be able to sustain 3/4 of each panel side area to allow lateral stability. This results in the recommendation of technical documentation and side barrier reinforcement.

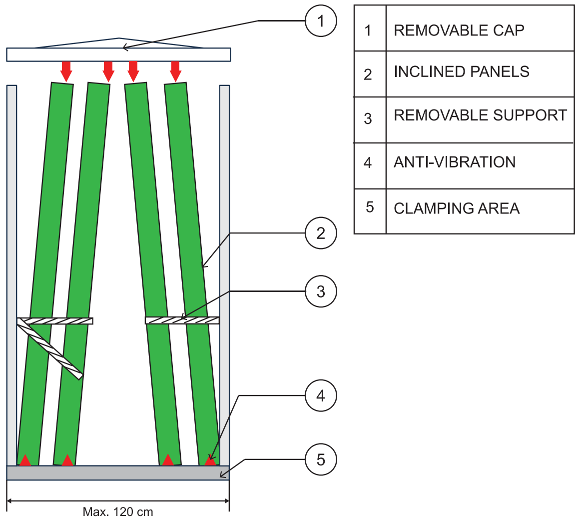


Figure 4- Detailed cross-section for rack design to meet the developed specifications

Table 3 - Validation of the suppliers' design against the rack design specifications developed in this paper

Drivers	Status	Actions Required / Remarks
D.5. Safety & Stability		
F.19. Secure Fastening Mechanisms	Incomplete	Clarification needed; tension strap may not suit inclined panels
F.20. Compliance with Safety Standards	Incomplete	Request technical documentation from the supplier.
D.2. Handling & Loading/Unloading		
F.6. Compatibility with lifting equipment (e.g., cranes, forklifts)	Compliant	Matches forklift specification
F.9. Time efficiency of securing and releasing façade panels from the rack	Unknown	Requires further testing through simulation.
F.10. Stability of the rack during lifting and handling	Unknown	Needs further experimentation or applying load simulations.
F.8. Ease of loading/unloading the rack onto transport vehicles	Compliant	Compatible with trailer dimensions
D.3. Transportation Conditions		
F.11. Vibration and Shock Resistance	Likely Compliant	Anti-vibration elements present
F.12. Weather Protection	Compliant	Meets all protective requirements
F.13. Trailer/Vehicle Compatibility	Compliant	Compatible with trailer dimensions
D.1. Panel Characteristics		
F.4. Panel Connector Type	Unknown	Integrated, but the time impact is unknown.

Incomplete · Compliant · Unknown · Likely Compliant

In terms of D.2, although the design is compatible with lifting facilities, as demonstrated by the presence of forklift pockets and conformity with standard specifications, the time taken for panel securing or releasing, and the stability when carrying out the lifting and handling processes, cannot be guaranteed without actual testing or physical simulations. The conditions within transportation (D.3) appear promising, as there should be no issues with vibrations and shock resistance due to the anti-vibration systems, such as rubber dampers and spacers. Compatibility with trailers follows a similar trend, and protective coverings ensure weather resistance. For D.1 compliance, it is observed that an integrated connector accommodation mechanism with minimal support features is provided; however, its consequences on handling time must be further tested.

6 Conclusions

This research outlines a systematic approach to rack system design specification that will help meet the needs of shipping modular façade panels within the Modular Integrated Construction (MiC) framework, facilitating stakeholder alignment regarding safety and efficiency in transportation solutions. A series of thorough literature review and industrial standards and guidelines, followed by surveys of experts (N=13), and statistical analysis, identified seven core decision drivers and 25 factors related to them, with Safety & Stability (Avg. 4.692), Handling & Loading/Unloading (Avg. 4.538) and Transportation Conditions (Avg. 4.462) being critical in steering the rack design towards efficient and safe logistics. These highlight the need to use racks that counter the risks of damage, displacement, and instability during transportation, thereby enhancing efficiency and fluidity of operation, while ensuring compatibility with standard equipment. Remarkably, the cost and budget variable (Avg. 2.69) was not a priority concern; instead, the experts focused on functional and robust specifications for the rack products, which was against the traditional procurement decision-making mechanisms based on prices.

Based on these findings, the designed rack specification guide includes non-negotiable parameters, such as the ability to securely fasten, dampen vibration, and provide modular adaptability, which helps deliver these benefits to undamaged customers and further smooth supply chains. A tiered classification approach based on mean scores and standard deviations ensures the framework's empirical robustness, as project teams can harmonise internal decisions with external supplier capabilities. This framework helps complement the larger body of sustainability in built environments by fostering material and emissions reductions, on-site risk mitigation of hazardous activities, and those by MiC, as well as efficiency and environmental stewardship. Theoretically, this study contributes to the knowledge of construction logistics by combining multidimensional aspects into a holistic and iterative perspective that fills gaps in real-time monitoring and multidisciplinary integration. The practical implications are that the proposed guideline provides a standardizable instrument for logistics planners, site managers, and manufacturers to create more effective policies on transportation standards and innovation in rack design. This study is limited by its small sample size and the focus on a single project context, which may restrict its generalizability. A larger survey of further geographies and regulations, the use of Round 2 expert opinion, and validation through fieldwork could be considered. This paper nevertheless demonstrates the radical nature of stakeholder-controlled specifications in streamlining MiC logistics, and as such, future renovations within cities can be achieved in a safer, more sustainable manner.

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Data Availability Statement
The data supporting this study's findings are available on reasonable request.

Conflicts of Interest
The authors declare that they have no conflict of interest.

References

Abeysinghe, A. M. G. P., K. G. A. S. Waidyasekara, and D. G. Melagoda. 2018. "Beyond Site Material Handling and Transportation in Large-Scale Construction Projects." Pp. 66–71 in *2018 Moratuwa Engineering Research Conference (MERCon)*. IEEE.

Arshad, Husnain, and Tarek Zayed. 2024. "A Multi-Sensing IoT System for MiC Module Monitoring during Logistics and Operation Phases." *Sensors* 24(15):4900. doi:10.3390/s24154900.

Attajer, Ali, and Boubakeur Mecheri. 2024. "Multi-Agent Simulation Approach for Modular Integrated Construction Supply Chain." *Applied Sciences* 14(12):5286. doi:10.3390/app14125286.

Bouwkamp, Philip M., Adam W. Dexter, and Steve Rumsey. 2007. "Pin Box Assembly with Torsion Resistant Pivot and Air Spring."

Brandín, Roberto, and Sepehr Abrishami. 2024. "IoT-BIM and Blockchain Integration for Enhanced Data Traceability in Offsite Manufacturing." *Automation in Construction* 159. doi:10.1016/j.autcon.2024.105266.

BSI. 2017. *Code XL: Vehicles with Regard to the Securing of Loads (BS EN 12642)*. London, UK.

CEN. 2010. *Load Restraining on Road Vehicles - Safety - Part 1: Calculation of Securing Forces (EN 12195-1: 2013)*. Brussels, Belgium.

Creswell, John W. .., and J. David. Creswell. 2018. *Research Design : Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications, Inc.

Gehring, Maximilian, and Uwe Rüppel. 2023. "Data Fusion Approach for a Digital Construction Logistics Twin." *Frontiers in Built Environment* 9. doi:10.3389/fbuil.2023.1145250.

ISO. 2013. *Series 1 Freight Containers — Specification and Testing — Part 1: General Cargo Containers for General Purposes (ISO 1496-1:2013)*. Geneva, Switzerland.

ISO. 2016. *Series 1 Freight Containers — Corner and Intermediate Fittings — Specifications (ISO 1161:2016)*. Geneva, Switzerland. https://www.iso.org/standard/65553.

Karaz, Mahmoud, and José Cardoso Teixeira. 2023. "Waste Elimination and Value Management Framework Based on Lean Design Methods." *Lecture Notes in Civil Engineering* 306 LNCE:334–45. doi:10.1007/978-3-031-20241-4_23.

Miklautsch, Philipp, and Manuel Woschank. 2023. "The Adoption of Industrial Logistics Decarbonization Practices: Evidence from Austria." *Transportation Research Interdisciplinary Perspectives* 21:100857. doi:10.1016/j.trip.2023.100857.

Miklautsch, Philipp, Manuel Woschank, and Julia Heißenberger. 2024. "Decarbonizing Construction Material Supply Chains: An Innovative Approach to Intermodal Transportation." *Lecture Notes in Civil Engineering* 390 LNCE:123–36. doi:10.1007/978-3-031-44021-2_14/FIGURES/2.

Montali, Jacopo, Mauro Overend, P. Michael Pelken, and Michele Sauchelli. 2018. "Knowledge-Based Engineering in the Design for Manufacture of Prefabricated Façades: Current Gaps and Future Trends." *Architectural Engineering and Design Management* 14(1–2):78–94. doi:10.1080/17452007.2017.1364216.

Niu, Sanyuan, Yi Yang, and Wei Pan. 2019. "Logistics Planning and Visualization of Modular Integrated Construction Projects Based on BIM-GIS Integration and Vehicle Routing Algorithm." *Modular and Offsite Construction (MOC) Summit Proceedings* 579–86. doi:10.29173/mocs141.

Patton, Michael Quinn. 2015. "Sampling, Qualitative (Purposeful)." in *The Blackwell Encyclopedia of Sociology*. Wiley.

Rammig, Lisa, Andrea Zani, Tim Murphy, Isabelle Paparo, Linda Hildebrand, Steve Abbring, Derick Kopreck, Christine Wu, Joyce Lee, and Kate Turpin. 2023. "Prefab Facades – From Prototype to Product? : The Kit-of-Parts Approach to a Facade Design." *Journal of Facade Design and Engineering* 11(1):61–75. doi:10.47982/JFDE.2023.1.04.

Saeed, Muhammad Atif, Muhammad Ahsan, Ashish Shiwlani, Ayesha Khan Nangraj, and Abdul Hannan. 2024. "Enhancing Efficiency and Safety in Self-Guided Logistics Vehicles: A Comprehensive Analysis and Integration of Hardware and Control Systems." *International Journal on Engineering, Science and Technology* 6(2):146–62. doi:10.46328/IJONEST.203.

Seghezzia, Elena, and Gabriele Masera. 2015. "Building Retrofit through Prefabricated Panels: An Overview on the State of the Art." *Anales de Edificación* 1(3):41–48. doi:10.20868/ADE.2015.3136.

Sheikhkhoshkar, Moslem, Hind Bril El Haouzi, Alexis Aubry, and Farook Hamzeh. 2024. "An Advanced Exploration of Functionalities as the Underlying Principles of Construction Control Metrics." *Smart and Sustainable Built Environment* 13(3):644–76. doi:10.1108/SASBE-12-2023-0379.

Sheikhkhoshkar, Moslem, Hind Bril El-Haouzi, Alexis Aubry, Farook Hamzeh, and Farzad Rahimian. 2025. "A Data-Driven and Knowledge-Based Decision Support System for Optimized Construction Planning and Control." *Automation in Construction* 173:106066. doi:10.1016/j.autcon.2025.106066.

Wang, Huiwen, Liang Liao, Wen Yi, and Lu Zhen. 2024. "Transportation Scheduling for Modules Used in Modular Integrated Construction." *International Journal of Production Research* 62(11):3918–31. doi:10.1080/00207543.2023.2251602.

Wang, Huiwen, Wen Yi, Lu Zhen, Haoqing Wang, and Albert P. C. Chan. 2023. "Automated Generation of Stacking Plans for Prefabricated Panels Transported by A-Frame Trailers." *Advanced Engineering Informatics* 57:102077. doi:10.1016/J.AEI.2023.102077.

Wehrli, Richard F. 2003. "Precast Concrete Panel Combination Trailer and Storage Rack Assembly." 1–16.

Yusof, Mohd Reeza, Mohd Nasrun Mohd Nawi, and Izatul Laili Jabar. 2023. "The Absence of Smart Technology as One of The Key Factors of Transportation in Modular Construction: A Case Study in Malaysia." *Advanced Research in Applied Sciences and Engineering Technology* 30(1):264–74. doi:10.37934/araset.30.1.264274.

Zelinska, Halyna, Lyudmyla Boldyrieva, and Iryna Amelina. 2018. "Logistic Quality Management of Transport Process in Construction." *International Journal of Engineering & Technology* 7(3.2):32. doi:10.14419/ijet.v7i3.2.14371.