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IDENTIFYING CRITICAL MANAGEMENT ACTIVITIES FOR OFF-SITE CONSTRUCTION SUPPLY CHAIN COORDINATION: AN IMPORTANCE-PERFORMANCE ANALYSIS APPROACH

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Abstract. Off-site construction (OSC) offers a transformative path toward faster, cleaner, and more consistent project delivery. Its success, however, depends on strong OSC supply chain coordination (OSC-SCC) across phases. Persistent fragmentation, unclear responsibilities, and reactive risk management continue to disrupt performance and constrain OSC's scalability. Prior research identifies critical risks, but often treats them in isolation, without a phase-based perspective on how coordination failures unfold or which management actions fall short. This study addresses these gaps by developing a structured, risk-responsive framework for OSC-SCC that (1) identifies critical risk categories and corresponding management activities across project phases; (2) evaluates their perceived importance and actual performance; and (3) clusters these activities to reveal cross-phase coordination gaps and inform targeted improvements. The analysis is grounded in importance-performance analysis, supported by expert surveys. Results reveal persistent underperformance in supplier incentivization, logistics traceability, responsiveness to demand changes, and process standardization. If left unaddressed, these issues cascade across phases, undermining efficiency and amplifying risks. The study contributes a practical tool that helps stakeholders align risk management with OSC's interdependent workflows. By translating risk insights into actionable, phase-aware strategies, the framework bridges theory and practice, supporting more resilient and scalable adoption of industrial construction.

Keywords: offsite construction, supply chain coordination, risk management, importance-performance analysis.

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1. Introduction

Off-site construction (OSC) represents a significant shift from traditional, site-based construction methods by relocating substantial portions of the building process to controlled factory environments (Lei et al., 2024). This approach involves the prefabrication of structural components, such as beams, columns, slabs, and fully volumetric modules, which are then transported to the site for final assembly (Jin et al., 2018; Innella et al., 2019). OSC offers well-documented benefits, including reduced construction time, improved safety, minimized material waste, enhanced quality control, and greater environmental sustainability (Tam et al., 2005). However, these advantages come with trade-offs. While OSC simplifies on-site execution, it simultaneously increases the complexity of upstream planning and coordination across the supply chain. The shift to off-site work demands tight synchronization between design, manufacturing, logistics, and on-site assembly, raising the stakes for effective supply chain coordination (Wang et al., 2019b). This has led to the emergence of Off-site Construction Supply Chain Coordination (OSC-SCC) as a critical performance factor due to its decentralized nature, fragmented coordination, misaligned responsibilities (Abdul Nabi & El-adaway, 2021; Wuni & Shen, 2020), and higher susceptibility to disruptions. These coordination issues often result in delays, rework, and cost overruns, ultimately limiting OSC's broader adoption and scalability.

Despite growing interest in OSC to improve speed, cost control, and efficiency, industry uptake remains inconsistent. The construction industry is undergoing a critical transformation, driven by a convergence of global pressures that make the need for resilient and well-coordinated OSC supply chains more urgent than ever. Sustainability imperatives are paramount, with the built environment responsible for nearly 40% of global CO_2 emissions. Prefabrication offers a tangible route to decarbonization by reducing material waste, improving energy efficiency through adaptive reuse of modular components (Wuni & Shen, 2020; Jayawardana et al., 2023; Li et al., 2024). Simultaneously, labor shortages are accelerating a shift from traditional site-based skilled trades toward automation and industrialized workflows, highlighting the need for a workforce equipped with digital competencies (Cheng et al., 2023). The post-pandemic context has further intensified the demand for scalable, fast-track delivery models, as seen in the deployment of modular healthcare facilities during COVID-19 and the consistent ability of OSC to deliver projects 30–50% faster (Zhang et al., 2024). Meanwhile, volatile global supply chains and stagnating productivity in conventional construction underscore the need for digitized and centralized coordination mechanisms to support logistics optimization (Li et al., 2024; Lopez et al., 2022). Despite these compelling drivers, the success of OSC implementation hinges on one underexplored factor: the ability to anticipate and manage supply chain risks through integrated coordination mechanisms. Current practices often address risks in isolation without understanding their cross-phase interactions. This study aims to strengthen OSC performance by advancing a phase-based understanding of supply chain risks and their risk mitigation. This research seeks to fill the gap in OSC literature by (1) Identifying and categorizing key risks across the phases of design, procurement, fabrication, and transport; (2) Assessing the importance and real-world performance of related risk management activities; and (3) Offering targeted recommendations to improve coordination, accountability, and planning within OSC-SCC frameworks. The novelty of this study lies in its integrative approach to developing actionable insights that link specific coordination challenges with distinct OSC phases. By doing so, the study contributes both conceptual clarity and practical guidance for improving supply chain resilience in the OSC projects.

2. Theoretical background

2.1. Risk management in OSC-SCC

This section is grounded in principles of Supply Chain Coordination (SCC) theory and risk management frameworks, which emphasize the importance of managing interdependencies, uncertainties, and process integration. Applying this lens to OSC, where teams and processes are distributed, provides a structured understanding of where and why coordination breaks down, especially in high-stakes environments with tight schedules, complex logistics, and high prefabrication intensity of critical materials. Effective SCC is foundational to OSC success, offering key advantages such as reduced inventory levels (Im et al., 2009), shorter lead times, enhanced client satisfaction, improved profitability (Arashpour et al., 2016), and promoting sustainability through waste reduction (Mao et al., 2015). However, the distributed and interdependent nature of OSC processes, spanning design, procurement, fabrication, and transport, introduces coordination challenges that are more intricate than those in traditional construction (Mostafa et al., 2016; Yang et al., 2020). Studies have identified recurring issues such as the absence of standardized specifications (Jiang et al., 2018), misalignments in prefabricated joint design (Cheng et al., 2023), and inadequate team communication, each contributing to cascading delays and quality lapses.

Recent literature has also emphasized that such disruptions frequently stem from resource misallocations during upstream planning. For instance, Si et al. (2021) and Xue et al. (2010) describe how poor coordination between design and procurement phases results in premature or delayed material orders, leading to inventory overruns or production hold-ups. Chang et al. (2017) highlight overlooked risks related to design incompatibility and supplier readiness, which are rarely anticipated early. These coordination breakdowns result in ineffective reactive management actions, such as rework or emergency rescheduling, rather than proactive risk mitigation (Arashpour et al., 2016). To address such risks effectively, a structured risk management process, comprising identification, analysis, response, and monitoring, is essential. Yet, in OSC, risk identification remains weak due to a lack of operational specificity (Hwang et al., 2013). Existing strategies often remain reactive and are not adapted to each phase of the project lifecycle. Risks such as late design changes (Zhang et al., 2024), procurement lead-time variability (Li et al., 2024), fabrication defects (Pan & Sidwell, 2011), and transport delays (Ma et al., 2022) are typically addressed in isolation rather than as part of an integrated risk response system. Without understanding how these risks interact or propagate across phases, mitigation efforts often fail to prevent downstream disruptions. Given the high capital intensity, stakeholder complexity, and time sensitivity of OSC projects, risk strategies must be context-sensitive, data-informed, and coordinated (El-Sayegh & Mansour, 2015; Zhao et al., 2016). Several studies have attempted to support such strategies by quantifying risk severity and frequency across construction phases. Wuni et al. (2023) evaluate the severity of risk events in Modular Integrated Construction, particularly during the onsite assembly stage. J. Jeong and J. Jeong (2022) rank 27 construction activities by analyzing fatal incident frequencies and probabilities, while Forteza et al. (2022) use Structural Equation Modeling to link site resource and complexity factors to observed risks. Gurcanli et al. (2015) apply L-matrix and Fine-Kinney methods to connect activity-level risks with safety costs in small residential projects, and Sanni-Anibire et al. (2020) use pairwise comparisons and six sigma tools to assign weighted risk scores. These studies provide critical insights into quantifiable risk attributes. While severity and frequency-based assessments offer valuable insights, there remains a need for approaches that better align risk evaluation with stakeholder priorities and operational performance gaps across OSC phases.

2.2. Evaluation of current management practices

Multiple risk management practices have been explored in the OSC-SCC context, ranging from logistics monitoring to supplier coordination and digital tool integration. Tools such as RFID and barcoding systems have enhanced visibility into material flows (Wang et al., 2019b), and digital scheduling platforms increasingly support coordination across dispersed teams. The integration of BIM, IoT, and AI-based monitoring reflects a shift toward Industry 5.0-enabled environments (Wang et al., 2020; Mortazavi et al., 2020; Xue et al., 2010). However, despite the technological potential, implementation remains inconsistent, and many of these tools are applied in isolation. Logistics-related risks are often addressed reactively, disconnected from upstream planning. As Liu et al. (2019) and Im et al. (2009) note, material flow breakdowns often result from the absence of integration between scheduling, procurement, and production, leading to rework and delivery mismatches. Moreover, real-time tracking systems are rarely embedded into upstream decision-making, such as lot sizing or production readiness (Zhang et al., 2024), resulting in missed opportunities to optimize coordination. While standardization of quality controls and component specifications is critical, these are inconsistently applied across projects (Yin et al., 2019). Hussein et al. (2021) and Bakhshi et al. (2022) show how delayed communication of design changes can cause rework, especially when teams operate from outdated documentation.

These findings demonstrate that while risk tools exist, their effectiveness depends on how well they are embedded within phase-specific workflows. Although performance-based contracts and incentive mechanisms are emerging (Simonsen et al., 2023; Raoufi & Fayek, 2018), many procurement processes still prioritize lowest-cost bids, exclude early supplier input, and enforce rigid scopes. This limits flexibility, weakens supplier relationships, and constrains innovation (Ballard & Tommelein, 2021; Gurca et al., 2021). As Sarhan et al. (2018) and Yang et al. (2020) note, manual procurement workflows still dominate, and digital procurement tools remain underutilized. Although techniques like JIT delivery and small-batch sourcing are recognized (Lo et al., 2018), they are rarely backed by procurement policies that support them. These limitations suggest that procurement risks are not just technical but structural, linked to outdated models. Addressing this gap is essential to bridge the disconnect between theoretical best practices and practical implementation, enabling more targeted and effective risk management strategies in OSC.

2.3. Research gap

The current body of research predominantly emphasizes technical solutions and tends to isolate risk factors without capturing the dynamic interactions between core project phases (design, procurement, fabrication, and transport). First, there is a less widely accepted, structured classification of OSC-specific risks mapped across project phases. Although several studies identify common risks, they rarely offer phase-specific groupings that enable actionable, targeted mitigation. This limits the development of customized risk responses and weakens planning precision. Second, most risk prioritization studies rely on likelihood and severity rankings but fail to assess how effectively those risks are being addressed in practice. This misalignment between importance and performance creates blind spots, where critical risks may be overlooked while low-impact issues consume resources (Almatroushi et al., 2020). Third, while the literature proposes best practices for areas such as logistics or procurement, empirical evaluation of these strategies is limited. Few studies identify which activities underperform and how practitioners perceive the success or failure of existing mitigation efforts. Fourth, existing research on coordination failures tends to examine individual project phases in isolation. Little attention is given to the interdependencies that connect decisions across the OSC supply chain. This study responds to these gaps by assessing how well existing risk mitigation practices align with the specific demands and interdependencies of OSC phases. By mapping and evaluating management activities, this study sims to offer a holistic view of OSC-SCC environments, bridging the fragmented nature and supporting more integrated, risk-informed planning.

3. Research design framework

3.1. Methodology

This study adopts a quantitative, exploratory research design, supported by structured expert surveys and importance-performance analysis (IPA), to examine coordination and operational risks in OSC supply chains. As illustrated in Figure 1, the research design is divided into three phases, combining literature review, data collection, and quantitative analysis. The overall process focuses on both understanding the importance of risks and evaluating the effectiveness of corresponding management activities. The methodology begins with the extraction of potential risks from existing literature related to OSC phases, design, procurement, fabrication, and transport. These risks were then organized into structured categories and translated into 40 distinct management activities under 11 broader management groups. This formed the foundation for developing IPA attributes. To validate and operationalize these findings, a survey was designed to collect expert ratings on the importance and performance of each activity through a 5-point Likert scale to measure professional judgment with substantial OSC-SCC experience. The collected responses provided the quantitative basis for analysis. Reliability of the data was tested using Cronbach's alpha to confirm internal consistency. The IPA results were then mapped onto a two-dimensional matrix to visualize how management activities and risk categories are distributed across the four quadrants, ranging from high-priority improvement zones to areas of overinvestment. This methodological framework ensures that critical gaps can be objectively identified and that recommendations are grounded in both theoretical rigor and expert insight.

3.2. Importance-performance analysis approach

IPA, first proposed by Martilla and James (1977), simultaneously compares, and evaluates the importance and performance of key project attributes to identify priority areas for improvement (Sever, 2015). In this process, attributes are identified, quantified, and visualized on a two-dimensional scatter plot, where their placement determines strategic priorities for resource allocation. Recent studies have demonstrated IPA's practical value in construction supply chain contexts. Wang et al. (2019a) applied IPA to assess critical risks in prefabricated buildings, such as component quality and factory management, revealing misalignments between perceived importance and actual management performance. Lee et al. (2023) used IPA to evaluate management activities across OSC construction phases, highlighting areas requiring performance improvement, especially in human resources and lifting operations. Alhawamdeh and Lee (2025) conducted a systematic review of OSC barriers, identifying integration issues that align conceptually with IPA's prioritization logic. The IPA method was selected for its clarity, intuitive visual framework, and practical relevance in complex project environments (Abalo et al., 2007). Unlike more computationally intensive techniques, IPA allows practitioners to map perceived importance against actual performance, facilitating rapid benchmarking and strategic prioritization. While AHP (Analytic Hierarchy Process) enables detailed pairwise comparisons, it requires extensive user input and consistency checks (Vaidya & Kumar, 2006). TOPSIS, although effective for ranking alternatives, lacks visual clarity and does not directly incorporate stakeholder perception (Zavadskas et al., 2016). FMEA (Failure Mode and Effects Analysis) emphasizes failure severity but does not evaluate actual performance or support holistic prioritization (Lipol & Haq, 2011). Given the fragmented responsibilities and cross-phase coordination challenges in OSC, IPA serves as an effective diagnostic tool that balances expert judgment with strategic resource planning. It is particularly suited for exploratory analysis where triangulating subjective perceptions and observed performance is critical to guiding improvements. Building on these efforts, this study advances the application of IPA by applying it to a comprehensive, phase-aligned dataset of management activities grouped into categories, spanning all four major OSC phases: design, procurement, fabrication, and transport. Unlike previous studies that focused on isolated phases or risk themes, this research offers an integrated, cross-phase evaluation of OSC coordination practices. By incorporating expert-validated indicators, internal reliability testing, and activity-level analysis, it provides a robust framework to prioritize performance gaps and reveal how coordination strategies can be optimized.

The IPA matrix in Figure 2 places each attribute on the importance-performance plane. The $y = x$ line represents 100% performance regardless of importance. Imbalance ($y \neq x$) signals resource-intensive improvements. The IPA graph divides the plane into four quadrants (Q1, Q2, Q3, and Q4). Q1 requires continuous maintenance due to its high importance and low performance. Q3 has low importance and performance, while Q2 needs intensive improvement despite its high importance. Q4 represents high performance but low importance, necessitating resource redirection (Ziegler et al., 2012). Grounded in the IPA framework, the following section initiates categorization to identify gaps that align with stakeholder priorities.

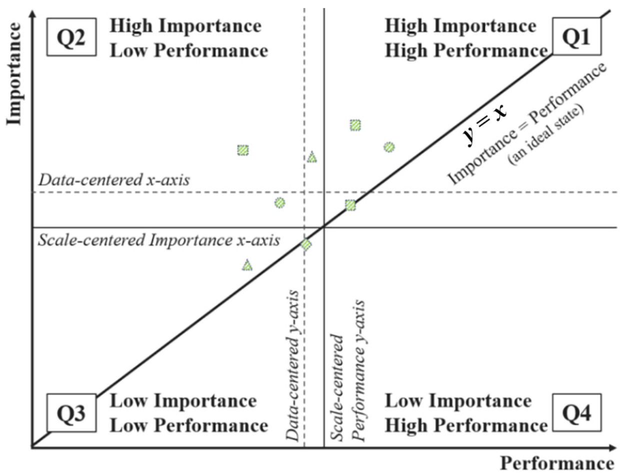

Figure 2. IPA matrix, derived from Ziegler et al. (2012)

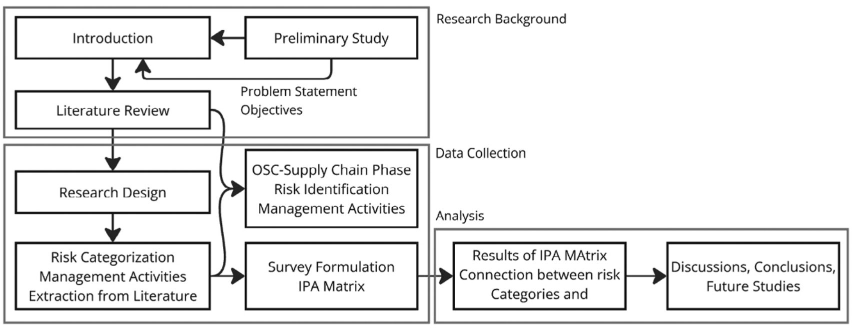

Figure 1. Research design

4. Extraction of risk categories and management activities based on OSC phases

4.1. Categorization of risks and management activities

This section outlines the initial stage of both risk identification and the IPA framework, where key risk factors relevant to OSC-SCC are systematically extracted from existing literature (see Appendix, Table A1). Risk identification involves uncovering uncertainties that may influence project outcomes, classifying them into relevant phases, and analyzing their impact on performance criteria such as time, cost, quality, and coordination. A structured extraction process, as illustrated in Figure 3, is conducted with a keyword-based screening using OSC-related terms (e.g., off-site construction, modular construction, prefabrication), risk-related terms (e.g., barriers, constraints, uncertainties, and risk management), and OSC phases terms (Design, fabrication, transportation, and procurement). The review focused on peer-reviewed articles published over the past 30 years in reputable construction and project management journals. Articles were selected based on the following criteria: (1) focus on internal operational project risks, excluding macro-level external events (e.g., pandemics, economic shocks); (2) alignment with core objectives such as cost, schedule, and quality; and (3) relevance to the design and execution phases of OSC-SCC. Through this screening, 85 relevant studies were identified and reviewed. The extracted risks were categorized into four primary OSC phases: Design, Procurement, Fabrication, and Transport, supporting targeted analysis and prioritization of mitigation strategies. Recognizing the impracticality of addressing all potential risks, the study focused on those with the greatest influence on long-term coordination and performance. These risks were synthesized into 40 management activities, grouped under 11 broader management categories. Many strategies shared similar application methods and targeted related aspects of risk categories rather than addressing entire risks comprehensively. Activities with similar functions were grouped to allow systematic evaluation of their performance relative to importance. This structured approach helps organizations identify key risk areas, determine which groups are most effective, and prioritize actions to allocate resources more efficiently and close performance gaps.

4.2. Interaction between risks in OSC phases and management activities

This section describes the risk factors and countermeasures for each aspect of an OSC phase: Design, procurement, fabrication, and transport.

Design Phase: In the OSC context, design-phase misalignment is one of the most influential risk factors impacting downstream execution. When critical inputs such as construction pre-requisites or technical detailing are not addressed early, it causes redesigns, delays, and incompatible sequencing with off-site production (Alhawamdeh & Lee, 2025). This creates major coordination gaps between design intent and project execution. Design changes made without real-time updates can cascade into significant rework during later stages (Yang et al., 2020). Another core challenge is the lack of supplier input during early planning. Without engaging key suppliers at the front end, opportunities to align on delivery goals, production constraints, and material specifications are missed (Kim & Rhee, 2024; Xue et al., 2010). Ineffective production planning also creates design-phase risks. Unbalanced task durations, missing data on critical resources, or unclear dependencies hinder workload leveling and delay execution. In response, simplified views of daily tasks and structured planning mechanisms should be developed early to support stable production. Moreover, updating the source plan and establishing a standardized process for quality assurance during the design stage is essential to avoid cascading downstream errors (Bakhshi et al., 2022). Timely development of a material delivery schedule and clear notification of demands help prevent misalignment and bottlenecks (Liu et al., 2019). Traceability on design changes and real-time material tracking must also be prioritized. Weak traceability reduces the ability to verify material flow and design conformance. Finally, transparency in scheduling and centralized oversight are necessary to ensure that all design outputs are aligned with construction planning and procurement execution (Liu et al., 2020).

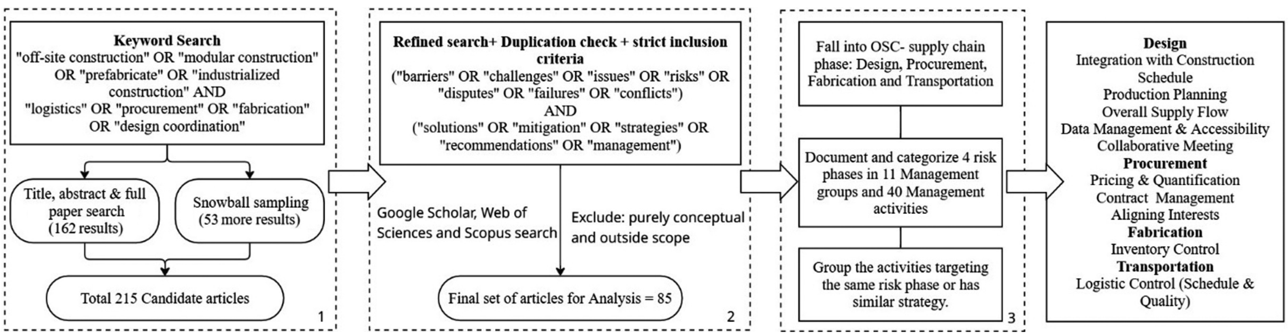

Figure 3. Risk extraction process: 1 – article identification; 2 – screening and eligibility; 3 – thematic categorization

Procurement Phase: Procurement risks in OSC projects often stem from fragmented planning, adversarial contract structures, and poor coordination with suppliers (Xue et al., 2010). Delayed ordering due to underestimate lead times disrupts production, while rigid budgets without contingencies increase vulnerability to price fluctuations, especially in volatile markets. Cost-reimbursable contracts and Bayesian models have been proposed to improve procurement efficiency by anticipating supplier bidding strategies (Wang et al., 2020). Traditional procurement often lacks performance-based incentives, reducing collaboration and innovation. Recent studies suggest integrating incentives, such as shared delivery data and dynamic scheduling, and penalties tied to delivery and quality performance to align stakeholder interests (Liu et al., 2020). Poorly enforced quality standards and vague contract terms further increase risks. Including inspection requirements and clearly defined roles and penalties strengthens supplier accountability. Finally, most traditional models do not support the integrated, fast-paced nature of OSC. Adaptive contracts that address coordination timelines, shared risks, and supplier engagement are essential for effective procurement across the OSC lifecycle (Im et al., 2009).

Fabrication Phase: In the fabrication phase of OSC projects, one of the most critical risks is the disruption of production flow due to poor coordination of material inputs (Bakhshi et al., 2022). Delays or shortages in required components directly affect the assembly line, leading to missed deadlines and increased operational costs. These disruptions are often caused by inaccurate inventory data or misalignment between schedules and fabrication requirements (Liu et al., 2019). Maintaining up-to-date and reliable inventory records is essential to manage material readiness and avoid workflow interruptions. In cases where inventory data is outdated or not integrated across systems, the risk of double ordering, missed shipments, or bottlenecks increases significantly. This affects not only production efficiency but also quality assurance and traceability of materials across suppliers and batches. The use of non-standardized or overly customized components is another risk factor. When parts vary widely in specification or source, it becomes difficult to maintain consistent quality across modular units (Innella et al., 2019). Standardizing component specifications and sourcing helps reduce variation and simplifies fabrication processes, leading to more predictable production outputs. A key management activity in this phase is the development and continuous updating of a material flow plan (Bakhshi et al., 2022). This plan should coordinate input schedules, fabrication timelines, and site delivery requirements. Without it, delays can occur due to mismatched production cycles, idle labor, or incomplete assembly batches. Clear planning improves fabrication stability and ensures readiness for shipping and installation. Limited or poorly organized inventory space, both at the fabrication facility and temporary staging areas, can result in overcrowding, misplaced materials, or delays in accessing necessary components (Liu et al., 2019; Im et al., 2009). Optimizing available storage space and applying JIT material strategies help avoid these issues, especially in high-volume production environments. Ultimately, efficient fabrication requires synchronized coordination between material availability, production capacity, and site readiness (Wang et al., 2019a). Without structured oversight, misalignment between these areas results in rework, idle resources, and downstream delays. A proactive approach that integrates data accuracy, flow planning, and standardized components is essential to reduce fabrication-phase risks.

Transportation Phase: The transportation phase is highly sensitive to coordination delays, material damage, and communication breakdowns. A common risk is last-minute order modifications that occur just before shipment, often leading to confusion, mislabeling, or missed loading deadlines. Timely communication of order changes is critical to allow logistics teams and carriers to adjust shipping plans without compromising the delivery timeline (Yang et al., 2020). Another significant issue arises from a lack of material control after receipt at the destination. Without verification and reconciliation of received materials, errors in quantity, condition, or labeling may go unnoticed, causing delays. Ensuring material control immediately upon arrival minimizes the risk of handover discrepancies and reduces downtime on-site (Liu et al., 2019). Limited visibility during shipping presents another layer of risk. When stakeholders lack real-time tracking, coordination between off-site production and on-site assembly becomes disjointed. Clear visibility into shipping progress helps anticipate delays, streamline staging, and align with installation crews (Liu et al., 2020). Shipping coordination failures also pose a high risk, especially in projects with multiple delivery batches. Inconsistent scheduling can lead to material congestion or idle teams waiting for specific components. Developing synchronized, milestone-based shipping schedules mitigates these risks and promotes effective site integration (Jin et al., 2018). Supplier traceability plays a critical role in managing quality and accountability during transport and tracing suppliers involved in production, ensuring transparency and enabling rapid response in case of defects or compliance issues (Ekanayake et al., 2021). Material protection during transit is another important consideration. Fragile or high-value components are vulnerable to damage without adequate protective layers. Applying extra safety measures, such as cushioning, wrapping, or weatherproofing, reduces the likelihood of rework. Finally, ongoing quality checks during transit help identify issues early in the logistics chain. Regular inspections at checkpoints assure that materials remain compliant with specifications (Abdul Nabi & El-adaway, 2021). These proactive strategies support a more reliable transportation process and reduce the risks at the final delivery.

While this study primarily evaluates risks and their mitigation activities, it also recognizes that many of these risks are interdependent. Delays or performance gaps in one phase, such as late design updates or demand notifications, can propagate to affect downstream activities, including procurement responsiveness, fabrication scheduling, and delivery logistics. These interlinkages are addressed through the expert surveys and analysis.

5. Survey of IPA method

5.1. Selection and scoring of IPA items

Following the categorization between the 4 risk phases, 40 management activities derived from the Extraction section are selected for the IPA measurement. The quantified items are the management activities categorized into 11 management groups.

Equations (1)–(3) were used to quantify and conduct IPA objectively:

Importance ($XR \# j$) or Performance ($XR \# j$) =

$$\frac{1}{N}\sum_{k=1}^{N}\left(XR\# j\right)_k; \tag{1}$$

Importance (XR) or Performance (XR) =

$$\frac{1}{M}\sum_{k=1}^{M}\left(\frac{1}{N}\sum_{k=1}^{N}\left(XR\# j\right)_k\right); \tag{2}$$

Importance (X) or Performance (X) =

$$\frac{1}{L}\sum_{k=1}^{L}\left(\frac{1}{N}\sum_{k=1}^{N}\left(XR\# j\right)_k\right), \tag{3}$$

where L is the number of management activities belonging to each risk category. The significance and effectiveness of management activities (represented as $XRi \# j$, where X = D, P, F, and T; $1 \le i \le 11$; and $1 \le j \le 40$), as well as the identified management groups and categories from the survey involving N experts, were determined using specific equations. N is the number of OSC-SCC experts, and M is the number of management activities belonging to each management group. The importance and performance of each management activity were computed using Eqn (1), which averaged the ratings provided by the N experts. Additionally, the importance and performance of each risk factor were calculated as the arithmetic average of the importance or performance scores of the management activities associated with that particular risk factor, employing Eqn (2). Equation (3) was used to calculate the importance and performance of each category. The dataset of the risk factors and the management activities is documented for analysis, as illustrated in Table 1.

Table 1. Reliability test of the dataset

	Design	Procurement	Fabrication	Transportation	Total
Importance	0.76	0.85	0.88	0.81	0.82
Performance	0.84	0.89	0.91	0.83	0.86

5.2. Survey and demographic overview

Expert-based surveys were chosen for their ability to capture contextual insights and practitioner-based judgment, especially in fields like OSC-SCC, where empirical data is often project-specific and limited in availability. The survey used a 5-point Likert scale to rate the importance and performance of 40 management activities, with 5 indicating “strongly agree”, 1 indicating “strongly disagree”, and 3 representing a neutral position. The survey was conducted online through Google Forms, and from the 95 distributed questionnaires, 58 valid responses were received, resulting in a 61% response rate. Participants were carefully selected based on their extensive experience in executing OSC-SCC projects within the industrial construction sector. The research participants are from various roles such as trade contractors (32.8%), fabricators (8.6%), quality control inspectors (20.7%), production managers (19%), and logistics managers (19%). The audience consisted of participants from the USA (75.9%), and Canada (24.1%). Demographic information revealed that 62.1% of participants had over 25 years of experience, and 22.4% had 20–25 years of experience in their roles. Moreover, a significant proportion (44.8%) had been involved in more than forty OSC-SCC projects, with 46.6% working on 31 to 40 relevant projects (see Appendix, Table A2). The survey included 80 questions to capture genuine opinions on the Importance and Performance of the 40 management activities. Participants lacking expertise in a specific management activity were instructed to leave the question unanswered, which were subsequently excluded and cleaned before the survey analysis. Given the survey participants from the USA and Canada, it is essential to recognize that the different contexts may shape the participants’ perspectives. The regulatory requirements and market conditions between these countries potentially lead to different prioritization of management activities. The results could be generalized with similar economies and professional demographics; however, a contextual comparison could be carried out for more robust context-specific insights.

6. Results

6.1. Reliability test of the dataset

Reliability testing is essential in quantitative research to assess the consistency and stability of measurement instruments. In this study, internal consistency was evaluated using Cronbach’s alpha, which reflects how closely related a set of items is as a group. Alpha values are influenced by the number of items, their interrelatedness, and dimensionality, with values between 0.70 and 0.95 generally considered acceptable. All risk categories in this study demonstrated strong internal consistency, with Cronbach’s alpha values ranging from 0.76 to 0.88 for importance and from 0.83 to 0.91 for performance. The overall reliability scores were 0.82 for importance and 0.86 for performance (Table 1), indicating that the survey items consistently measured the intended constructs across all phases of OSC.

6.2. Results of the IPA matrix for management groups and activities

Table 2 presents the IPA survey results, detailing each activity alongside its corresponding importance and performance ratings as provided by the expert respondents. The study analyzed 40 management activities, with most around an average importance of 4.0 and a mean performance of 2.7 (Figure 4). Most activities fall in the Q2 quadrant. F#24 and F#35 showed balanced importance and performance, being closest to the $y = x$ line. However, D5#19 exhibited the highest difference between importance (4.759) and performance (1.931), far from the $y = x$ axis. Figure 5 analyzed 11 management groups with an average importance of 4.1 and performance of 2.9. Groups such as D3, D5, P3, T1, and T2 exhibited significant discrepancies between their importance and performance ratings, appearing furthest from the $y = x$ line, indicating notable performance gaps. In contrast, P2 was positioned in Q4, reflecting a relatively high performance score (4.423) paired with lower perceived importance (2.868), suggesting potential overinvestment. The following section provides a detailed phase-wise analysis of these findings across the OSC-SCC lifecycle.

Table 2. Importance and performance survey results

Management Activities	Importance	Performance	Management Activities	Importance	Performance
Design Phase (D)			Procurement Phase (P)		
Integration with Construction Schedule (D1)			Pricing & Quantification (P1)		
Involve suppliers in contractor's planning (D1#1)	4.034	2.603	Assess SC costs (P1#21)	4.000	2.603
Establish pre-requisites to construction (D1#2)	3.759	4.356	Identify, Assess, Aggregate product resource (P1#22)	3.690	2.862
Detailing in critical path (D1#3)	3.983	2.517	Negotiate Price when inflation (P1#23)	3.707	4.897
Implement change plan (D1#4)	4.241	2.741	Contract Management (P2)		
Production Planning (D2)			Allow extra funds (P2#24)	3.793	4.017
Resource levelling (D2#5)	4.052	2.672	Allow adequate time in procurement (P2#25)	2.241	4.356
Task duration (D2#6)	3.931	2.793	Contract includes Commission inspection (P2#26)	2.569	4.897
Critical resources (D2#7)	4.000	2.776	Aligning Interests (P3)		
Simplified View of daily tasks (D2#8)	3.987	3.121	Incentive to suppliers (P3#27)	4.224	2.259
Overall Supply Flow (D3)			Potential penalty (P3#28)	4.224	2.172
Updating source plan (D3#9)	4.310	2.483	Fabrication Phase (F)		
Standardized process for quality (D3#10)	4.397	2.397	Inventory Control (F1)		
Material delivery schedule (D3#13)	4.724	3.560	Maintain safety stock (F1#29)	4.103	2.293
Small, frequent orders (JIT) (D3#12)	3.931	2.086	Accurate inventory data (F1#30)	3.862	2.707
Notify demands early (D3#13)	3.914	2.724	Standard components (F1#31)	3.931	2.552
Expedite materials (D3#14)	3.707	3.034	Create + Update material flow plan (F1#32)	3.776	3.500
Data Management & Accessibility (D4)			Optimize inventory spaces (F1#33)	4.448	2.241
Material tracking (D4#15)	4.207	2.466	Transportation Phase (T)		
Traceability on Design Change (D4#16)	4.069	2.500	Logistic Control (Schedule) (T1)		
Transparency in schedule (D4#17)	2.569	4.034	Notify order changes timely (not right before shipping) (T1#34)	4.379	2.069
Immediate response (D4#18)	2.345	4.897	Gain material control after receipt (T1#35)	3.603	3.578
Collaborative Meeting and Correspondence (D5)			Visibility in shipping (T1#36)	4.500	2.172
Integrate decision-making (D5#19)	4.759	1.931	Logistic Control (Quality) (T2)		
Improve collaboration (D5#20)	4.247	2.495	Coordinate Timely shipping (T2#37)	4.897	3.500
			Trace suppliers (tiers of suppliers involved in the production process) (T2#38)	3.828	2.483
			Frequent quality checks (during shipping) (T2#39)	4.603	3.578
			Extra safety (layer protection) (T2#40)	4.259	2.000

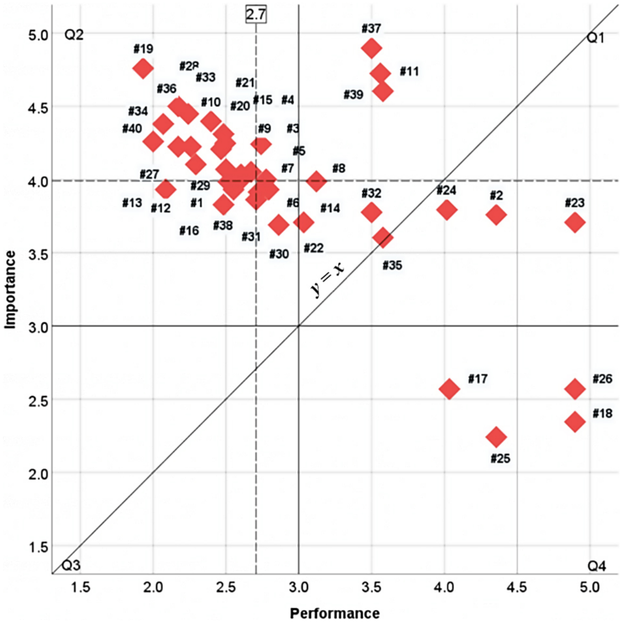

Figure 4. IPA graph of 40 management activities

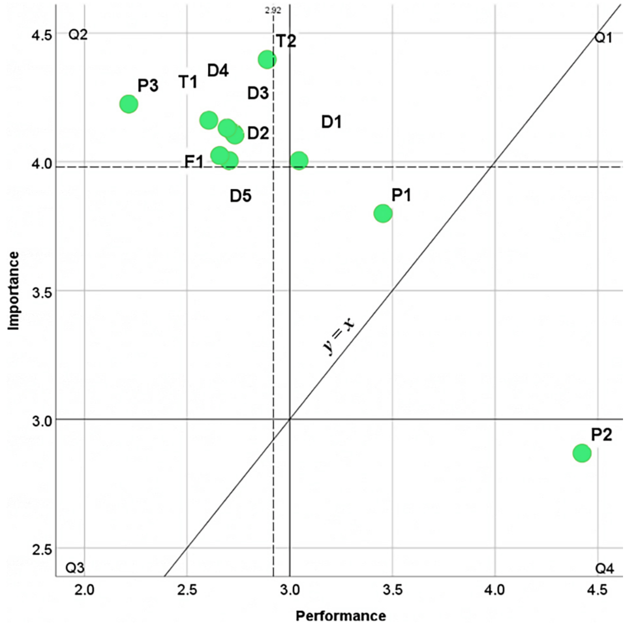

Figure 5. IPA matrix of all management groups

6.3. IPA matrix of each risk category in OSC phase

In Design Phase (D), as illustrated in Figure 6, survey participants rated the Design phase management activities with an average importance of 3.95 and performance of 2.90. Among the 20 management activities, 17 were rated highly important but showed significantly low performance, placing them in Q2. Eleven of these also appeared in Q1. Activity D1#2 had higher performance than importance, plotted below the $y = x$ axis. Activities D2#8 and D3#14 were relatively well-balanced, positioned close to the $y = x$ line. In the Data Management and Accessibility group, out of four activities, D4#17 and D4#18 were in Q4, indicating higher performance than importance and suggesting potential resource overinvestment. In contrast, D4#15 and D4#16 were in Q2, indicating a need for intensive improvement. The importance of these activities ranged from 2.3 to 4.8, while performance values ranged from 1.9 to 4.9. Among them, D5#19 had the highest importance (4.759) and lowest performance (1.931), plotted farthest from the $y = x$ axis. Similarly, D5#20 showed a significant difference between importance (4.247) and performance (2.495).

The IPA index of Procurement (P) category (Figure 7) shows importance ranging from 2.2 to 4.2 and performance from 2.1 to 4.9. Among 8 management activities, 4 are in Q2 (higher importance, lower performance), 2 in Q1 (continuous maintenance needed), and 2 in Q4, indicating resource overinvestment. Notably, P2#25 has the highest performance (4.356) and lower importance (2.241), while P2#26 has the most outstanding performance (4.897) and lowest importance (2.569). On the other hand, P3#27 and P3#28 require intensive improvement, each showing a significant gap between high importance (4.224) and lower performance, with P3#27 at 2.259 and P3#28 at 2.172, the lowest in the Procurement category. P2#24 shows balanced importance (3.793) and performance (4.017), closer to the $y = x$ line. Among the Q2 quadrant activities, P1#21 and P1#22 also exhibit significant differences between importance and performance, with P1#21 rated highly important (4.000) and low in performance (2.603), and P1#22 showing a similar gap with an importance of 3.690.

Figure 8 illustrates the IPA matrix for the Fabrication phase, with an overall average importance of 4.024 and performance of 2.659. Most activities are located in Q2, indicating high importance, but low performance, suggesting a need for targeted improvements. F1#33 (Optimize inventory spaces) shows the widest gap, with the highest importance (4.448) and lowest performance (2.241). F1#29 (Maintain safety stock) also reflects a significant gap (importance: 4.103; performance: 2.293), followed by F1#31 (Standard components) and F1#30 (Accurate inventory data), both showing performance below 2.8 despite high importance. In contrast, F1#32 (Create and update material flow plan) appears near the $y = x$ line with relatively aligned scores (3.776 and 3.500), indicating more effective implementation compared to other activities.

Figure 9 shows the IPA matrix for the Transportation phase with schedule-related activities (T1) having an average importance of 4.161 and performance of 2.606, while quality-related activities (T2) averaged 4.397 and 2.890, respectively. T1#36 (Visibility in shipping) and T1#34 (Notify order changes timely) show significant gaps, with high importance (4.500 and 4.379) and low performance (2.172 and 2.069), placing them in Q2. T2#40 (Extra safety layer protection) also shows a wide gap (importance: 4.259; performance: 2.000), along with T2#38 (Trace suppliers), which scored 3.828 in importance and 2.483 in performance. In contrast, T2#37 (Coordinate timely shipping) and T2#39 (Frequent quality checks) demonstrate strong alignment, both falling into Q1 with high performance.

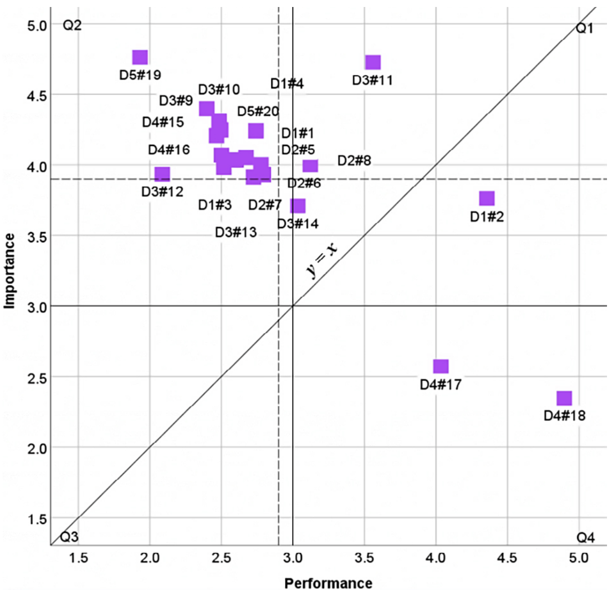

Figure 6. IPA matrix of Design (D) category

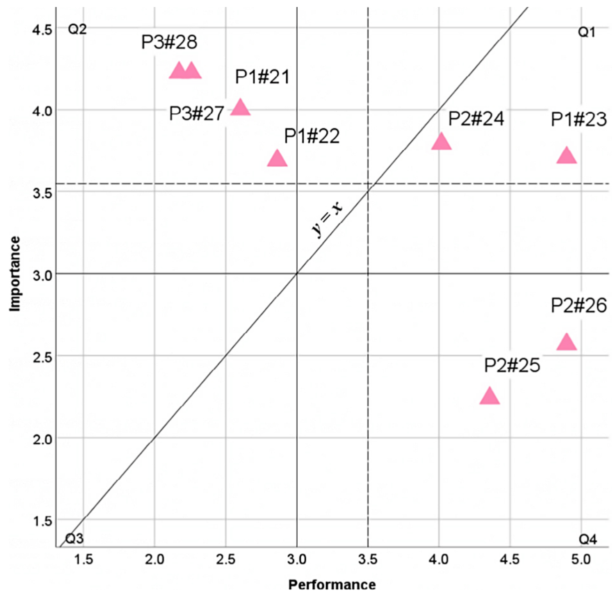

Figure 7. IPA matrix of the Procurement (P) category

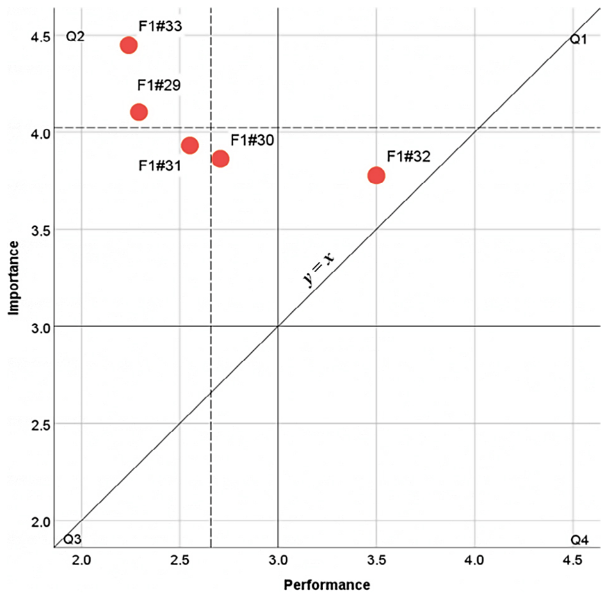

Figure 8. IPA matrix of Fabrication (F) category

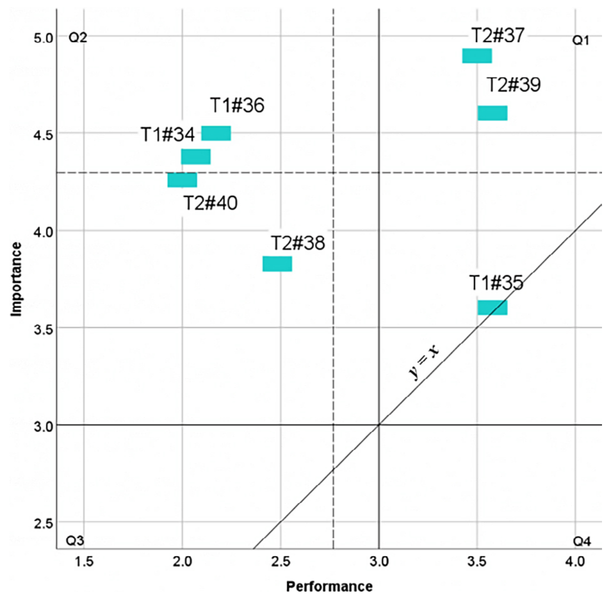

Figure 9. IPA matrix of Transportation (T) category

T1#35 (Gain material control after receipt) is near the $y = x$ line, indicating balanced execution. The phase-wise IPA results highlight critical performance gaps across OSC activities, providing a foundation to explore how these risks interact and impact coordination.

7. Discussion

The analysis identifies that many OSC coordination risks are interrelated and often propagate across phases. For example, delayed demand notifications in procurement can disrupt fabrication scheduling and trigger transport inefficiencies. These cross-phase interactions, while not the central unit of analysis, are captured through grouped management activities, reinforcing the systemic nature of OSC-SCC risks.

7.1. Identification of the OSC-SCC key risks and strategies

This section addresses the study objectives by identifying key OSC-SCC risks and strategies for effective mitigation and control, discussing mitigation strategies and systematic activity groups corresponding to each risk category, emphasizing necessary corrective measures, and valuating management activity performance and suggesting improvements. The IPA matrix reveals ten critical management activities with notable discrepancies between their importance and performance values. These activities include 'Standard Components' (F1#31), 'Standardized Process for Quality' (D3#10), 'Notifying Demands Early' (D3#13), 'Notify Order changes timely' (T1#34), 'Visibility in Shipping' (T1#36), 'Trace Suppliers (Tiers of suppliers involved in the production process)' (T2#38), 'Integrate Decision-Making' (D5#19), 'Improve Collaboration and Correspondence' (D5#20), 'Incentives to Suppliers' (P3#27), and 'Potential Penalties' (P3#28). This suggests that by minimizing the imbalance between these prioritized activities, risks in the OSC-SCC can be mitigated.

7.2. Standardization of components and processes for OSC-SCC excellence

'Standard Components' (F1#31) and 'Standardized processes for quality' (D3#10) have higher mean importance (4.164) and lower mean performance (2.475) plotted in the Q2 quadrant, stating they need intensive improvement strategies. Low standardization can be considered one of the most critical barriers to OSC adoption. To bridge the gap, several authors provide technical guidelines for OSC adoption in terms of design, installation, construction, and operation. The production norms, quality criteria, and OSC standards are still lacking. A study by Jayawardana et al. (2023) revealed that utilizing standard components can decrease product development lead time, while Azambuja et al. (2014) summarize preparing project-level strategy and supply plans based on information from commodities managers. Studies suggest strategies that the preliminary project supply plans may include decisions on standardization, modularization, on-site versus off-site fabrication, master schedule, contracting strategy, and the scope of responsibility, to improve the performance of the Overall Supply Flow plan (D3).

7.3. Enhancing responsiveness to demand and order changes through timely notifications

From the survey results, 'Notify demands early (D3#13)' and 'Notify order changes timely (T1#34)' are plotted in the Q2 quadrant with a mean importance of 4.146 and a lower mean performance of 2.396, indicating a need for an implementation plan. Recent studies confirmed that frequent delivery due to changes harms a supplier's production scheduling, with the production costs (T. Kim & Y. Kim 2022; Kim et al., 2020). Kim et al. (2020) highlighted that, considering due date uncertainty, advanced production scheduling could offer a systematic approach to handling uncertainties while improving the reliability of the supply chain. Additionally, Kim et al. (2021) highlight the adoption of dispatching rules like the early due date, short processing time, and critical ratio to enhance the scheduling of OSC products, contributing to streamlined operations. There is a need for planning and integrated systems to identify material shortages early and take corrective actions. Li et al. (2024) discuss the bullwhip effect caused by delays in demand information, emphasizing the importance of early demand notification and synchronized planning. T1#34 is farthest from the $y = x$ line; therefore, late order changes pose a significant risk in OSC projects, leading to cost overruns. It is suggested to create a timely notification of changes within a buffer time and not right before the shipping or assigning a design freeze before initiating module manufacturing to improve the Logistic Control.

7.4. Leveraging supplier traceability and shipping visibility for effective logistic control

Several studies aligned with the IPA results emphasize the critical role of material quality and recommend methods to address uncertainties within the logistics network. Activities such as 'Visibility in Shipping' (T1#36) and 'Trace Suppliers (Tiers of suppliers involved in the production process)' (T2#38) are positioned in the Q2 quadrant, highlighting a discrepancy between their significance and actual performance. A proposed risk management framework for logistics planning involves improving visibility into shipping statuses and accessing material information directly from suppliers to prevent scheduling errors. Enhancing transparency in transportation schedules can mitigate negative impacts on delivery lead times and supply chain coordination. This study advocates balancing the performance of logistics control by improving material and technology data collection from suppliers and ensuring transparent information flow.

7.5. Integrating decision-making and supplier collaboration

The survey respondents rated the mean importance value of 'Integrating decision-making' (D5#19), 'Collaborative Meetings and Correspondence' (D5#20), and 'Involve suppliers in contractor's planning' (D1#1), plotted in Q2 quadrant, suggesting a requirement for a strategy to bridge this gap. To support efficient information sharing, the integration of BIM and RFID technology is recommended to facilitate real-time progress monitoring and aid in process management. In line with the survey results, long-term collaboration is crucial to managing the conflicts in OSC-SCC, characterized by close relationships between stakeholders. To optimize the stakeholder relationship, Kim and Nguyen (2018) provided a structural model to identify supply chain relationship traits and assess their impacts on performance. Since the survey analysis concludes that there is a need for corrective action, establishing an information-sharing channel throughout the entire project duration is essential, including manufacturing and transporting parts and field assembly details. Ekanayake et al. (2021) propose the inclusion of suppliers and transporters in the contractor's planning process to improve delivery planning by reducing uncertainties and enhancing coordination. Additionally, strategic supplier agreements that prioritize supplier integration as a competitive advantage, as suggested by Azambuja et al. (2014), advocate for involving critical component suppliers during conceptual stages, which can help in reducing engineering effort and rework. Combining survey findings and insights from studies, promoting collaboration, leveraging advanced technologies, and involving key stakeholders are essential strategies to reduce disputes and ensure long-term partnerships in the OSC projects.

7.6. Incentivizing delivery delay and penalty scheme for suppliers

Overall, the Procurement (P) category shows balanced IPA values. However, according to the literature and the survey respondents, there is a subsequent gap in 'Aligning the Interests' (P3) with mean Importance (4.224) and mean Performance (2.216). A notable difference emerges between 'Incentive to suppliers' (P3#27) and 'Potential penalty' (P3#28) as compared to other activities in this category since they are plotted farthest from the $y = x$ line suggesting that they are identified as a priority, but no proactive measures or resources are allotted for the improvement. Si et al. (2021) propose a dynamic and distributed solution involving incentives provided by manufacturers through an information-sharing platform to promote timely delivery by allowing contractors to automatically adjust plans based on manufacturers' data and on-site resources. Kim and Rhee (2024) propose a mathematical model to calculate incentives to a contractor to improve demand reliability. Liu et al. (2020) present a different perspective on a penalty scheme for suppliers that considers delivery time and material quality to incentivize suppliers to enhance their performance and reduce delays. The first approach is proactive; it seems to be highly valued, but the implementation requires enhancement, while the other suggestion proposes to drive supplier performance, suggesting room for improvement in effectively enforcing penalties.

7.7. Other critical management activities

It is important to note that while these management activities are not strictly categorized as supply chain coordination risks, they are critical in the overall OSC-SCC process. The study by Liu et al. (2019) underscores the importance of 'Maintaining Safety Stocks' (F1#29) in managing inventory levels during longer lead times. The findings suggest that organizations should maintain safety stocks to accommodate unexpected increases in demand or delays. Survey results place F1#29 in the Q2 quadrant, indicating high importance but lower performance. This implies that, while maintaining safety stocks is recognized as essential, their execution requires enhancement. To optimize safety stock performance, organizations may need to implement strategies for demand forecasting, establish reliable supplier relationships, and adopt an inventory management technique. Furthermore, studies have identified significant transportation risks and emphasize the importance of additional safety measures to prevent damage during shipping, packaging, handling, and storage uncertainties. This study reveals that Extra safety (T2#40) has high importance but low performance, indicating an urgent need to incorporate extra protection layers to mitigate transportation risks. Several authors propose utilizing innovative technologies for efficient movement between factories and sites by including budget allocation and a review of transportation technologies to enhance component quality.

8. Limitations

This study has several limitations that present opportunities for future research. First, the list of risk categories and management activities should not be viewed as exhaustive. Future research could explore how these gaps influence decision-making and coordination. Second, examining case studies of successful incentive mechanisms and linking them to correlation analysis could offer insights into the conditions that drive positive outcomes. Third, a longitudinal study could evaluate the long-term impacts of these management activities, particularly under varying external conditions such as market volatility. Finally, future studies could explore risk classification frameworks by categorizing risks as strategic, operational, or external, to yield new dimensions of analysis.

9. Conclusions

Off-site construction (OSC) is transforming the building industry by enabling faster delivery, reduced waste, and improved quality through prefabrication. However, its full potential is hindered by persistent supply chain coordination (SCC) challenges, including misaligned responsibilities and reactive risk management. This study provides a structured framework to identify and evaluate critical OSC-SCC management activities across design, procurement, fabrication, and transportation phases. Using Importance-performance analysis (IPA), the research highlights key underperforming but high-priority areas, such as standardization, early demand notification, supplier collaboration, and logistics visibility that require targeted improvements. Conversely, it also identifies areas of potential overinvestment. The IPA tool enables evidence-based decision-making by aligning resource allocation with stakeholder priorities and operational performance gaps. By offering a phase-specific, risk-informed view of OSC coordination, this study bridges the gap between theoretical best practices and real-world execution. The proposed strategies can support more resilient, collaborative, and scalable adoption of OSC, contributing to sustainable construction outcomes and improved project performance.

Disclosure statement

The authors declare no conflicts of interest.

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APPENDIX

Table A1. Risk categorization

OSC Phases	Management Activities	Management Group
Design (D)	Involve suppliers in contractor's planning (D1#1) Establish pre-requisites to construction (D1#2) Detailing in critical path (D1#3) Implement change (D1#4)	Integration with Construction Schedule (D1)
	Resource leveling (D2#5) Task duration (D2#6) Critical resources (D2#7) Simplified View of daily tasks (D2#8)	Production Planning (D2)
	Updating Source plan (D3#9) A standardized process for quality (D3#10) Material delivery schedule (D3#11) Small, frequent orders (JIT) (D3#12) Notify demands early (D3#13) Expedite materials (D3#14)	Overall Supply Flow Plan (D3)
	Material identification, tracking and locating (D4#15) Communicating on Design Change (Traceability of material flow) (D4#16) Transparency in schedule (D4#17) Immediate response (D4#18)	Data Management & Accessibility (D4)
	Integrate decision-making (D5#19) Improve collaboration (D5#20)	Collaborative Meetings and Correspondence (D5)
Procurement (P)	Assess SC costs (P1#21) Identify, Assess, and Aggregate product resource (P1#22) Negotiate Price when Inflation (P2#23)	Pricing & Quantification (P1)
	Allow extra funds (P2#24) Allow for Adequate time in procurement (P2#25) Contract includes Commission inspection (P2#26)	Contract Management (P2)
	Incentive to suppliers (P3#27) Potential penalty (P3#28)	Aligning Interests (P3)
Fabrication (F)	Maintain safety stock (F1#29) Accurate inventory data (F1#30) Standard components (F1#31) Create + Update material flow plan (F1#32) Optimize inventory spaces (F1#33)	Inventory Control (F)
Transportation and Logistics (T)	Notify order changes timely (not right before shipping) (T1#34) Gain material control after receipt (T1#35) Visibility in shipping (T1#36)	Logistic Control (Schedule) (T1)
	Coordinate Timely shipping (T2#37) Trace suppliers (suppliers involved in the production) (T2#38) Frequent quality checks (during shipping) (T2#39) Extra safety (layer protection) (T2#40)	Logistic Control (Quality) (T2)

Table A2. Demographics of survey participants

1. What is your job role in the Off-site Construction work industry?		Frequency	Percent	Cumulative Percent
Valid	Fabricator (Workforce)	5	8.6	8.6
	Logistics Manager	11	19.0	27.6
	Production Manager	11	19.0	46.6
	Quality Control Inspector	12	20.7	67.2
	Trade Contractor	19	32.8	100.0
	Total	58	100.0	
2. How many Off-site Construction projects were you involved in, where you worked on their Supply chain Coordination?		Frequency	Percent	Cumulative Percent
Valid	11 to 20 Projects	3	5.2	5.2
	21 to 30 Projects	2	3.4	8.6
	31 to 40 Projects	27	46.6	55.2
	More than 40 projects	26	44.8	100.0
	Total	58	100.0	
3. Which country you have been working in the job role mentioned?		Frequency	Percent	Cumulative Percent
Valid	Canada	14	24.1	24.1
	United States of America	44	75.9	100.0
	Total	58	100.0	
4. How many years of work experience do you have in the above-mentioned job role?		Frequency	Percent	Cumulative Percent
Valid	10–15 years	3	5.2	5.2
	15–20 years	6	10.3	15.5
	20–25 years	13	22.4	37.9
	More than 25 years	36	62.1	100.0
	Total	58	100.0	