



Review

Managing Black Swan Event Risks in the Construction Supply Chain: A Literature Review

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Abstract

Disruptive global events such as the COVID-19 pandemic have exposed critical vulnerabilities in the construction industry's reliance on lean principles and Just-In-Time (JIT) methodologies. These disruptions, categorized as Black Swan Events (BSEs), challenged conventional supply chain management (SCM) and risk management (RM) strategies, resulting in delayed projects and increased costs. This paper explores how BSEs affect construction supply chains and evaluates the industry's evolving response through RM and resilience-building strategies. A Joanna Briggs Institute (JBI) scoping review of the literature (2000–2024) synthesized evidence across SCM, RM, Lean Construction, JIT, and BSEs, triangulating 86 peer-reviewed studies with authoritative industry reports. The review reveals a lack of integrated research addressing these themes holistically for the construction sector. Key findings show that while JIT and lean approaches optimize efficiency, they fall short during high-impact, low-probability disruptions. Evidence indicates a selective shift toward Just-In-Case (JIC) practices; however, the extent and persistence of this transition vary by project context and merit further study. The study proposes a future research agenda emphasizing interdisciplinary models that integrate lean methods with resilience and anticipatory strategies. These insights aim to support construction firms in developing supply chains that are not only efficient but also adaptable and better prepared for future BSEs.

Keywords: Black Swan Events; construction supply chain; Just-in-Time; risk management; resilience



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1. Introduction

The construction sector plays a vital role in economic development, urbanization, and the delivery of infrastructure [1]. However, unlike manufacturing, it operates through a project-based model with high variability and low repetition, leading to complex supply chains and increased risk exposure [2–7]. Because each project is unique and highly dependent on external coordination, construction projects require synchronization among numerous actors and timely delivery of globally sourced materials and equipment, leaving them particularly vulnerable to disruption. Recent construction-specific literature also flags a persistent gap: limited availability of an industry-specific supply-chain risk taxonomy tailored to construction's site-specific conditions, regulatory constraints, and multi-stakeholder structure [8].

Supply chain risks in construction encompass delays, material shortages, demand fluctuations, and external shocks such as geopolitical tensions or natural disasters [9].

The traditional focus on optimizing supply chains through lean principles, notably JIT methodologies, aimed to minimize waste, reduce costs, and streamline delivery [10,11]. While JIT contributed to operational efficiencies, it also reduced inventory buffers and increased reliance on precise timing, leaving the sector particularly exposed during periods of global instability [12,13].

Recent disruptions have exposed these vulnerabilities on an unprecedented scale. BSEs (rare, unforeseeable, high-impact occurrences) profoundly impacted global and construction-specific supply chains [14–16]. In this paper, BSEs are defined as low-probability, high-impact disruptions that are difficult to anticipate using historical data. We distinguish these from “known” or emerging operational risks that can be quantified and managed through standard project controls. When events overlap both categories (such as pandemics, chokepoint blockages, or geopolitical crises) they are classified based on their uncertainty profile and impact mechanism, with emphasis on construction-specific consequences.

Figure 1 illustrates this relationship using a probability–impact matrix, where typical project risks appear in the midrange, while BSEs occupy the upper-left corner, representing extremely low probability but catastrophic impact.

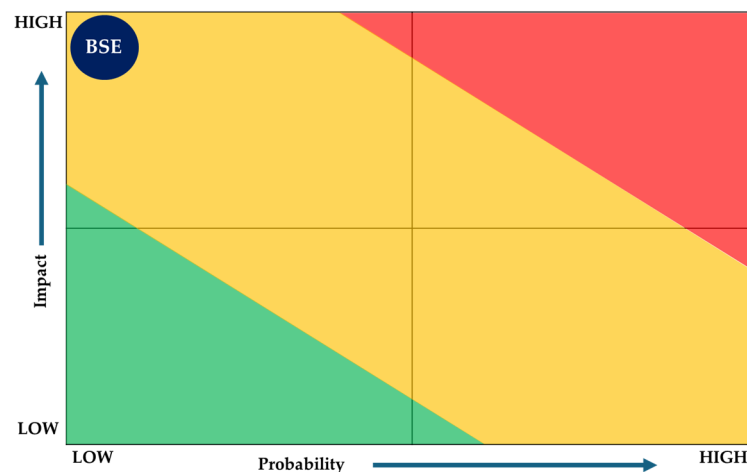


Figure 1. Probability–Impact Matrix illustrating the position of BSEs relative to normal and emerging risks. (Green: Low, Yellow: Medium, Red: High).

The COVID-19 pandemic disrupted material sourcing, caused labor shortages, and halted construction activities across multiple regions [17]. Lockdowns, factory shutdowns, and border closures triggered cascading failures across interdependent supply networks [18,19]. Construction-focused studies have reported similar cascading effects, including project shutdowns, subcontractor insolvencies, and severe delays in critical materials such as switchgears and prefabricated assemblies, confirming the disproportionate impact of COVID-19 on construction supply chains [20–24].

Jin et al. (2021) further detailed how pandemic control measures translated into operational breakdowns at the project level, linking supply-chain interruption, workforce unavailability, schedule delay, and cost escalation as interdependent outcomes rather than isolated risks [25]. Local suppliers and home-improvement retailers also experienced major operational disruptions including demand surges, supply shortages, labor constraints, and rapid shifts toward curbside pickup, as documented by Murray [26].

Separately, the 2021 blockage of the Suez Canal highlighted global supply chain vulnerabilities by disrupting an estimated \$9 billion in daily trade [27,28]. In the construction sector, delays in the delivery of prefabricated modules, electrical components, and mechanical equipment were reported, demonstrating the industry’s dependence on uninterrupted maritime logistics [27,29–31].

In addition, the Russia–Ukraine conflict triggered shortages of critical construction materials, further straining global construction supply chains and compounding the effects of earlier disruptions [32–34]. Empirical studies confirm that the conflict caused shortages of steel, aluminum, and electrical components, significantly increasing procurement lead times and project costs across multiple regions [34–39].

Industry reports reinforced these findings, Deloitte [40], Skanska [41,42], and DPR [43] documented how construction supply chains failed to absorb shocks during these events, emphasizing the urgency for resilience and adaptability. Recent global-scale analyses similarly argue that organizations strengthen long-term supply chain survival by developing resilience capabilities that enable them not only to withstand Black Swan disruptions but also to adapt and thrive amid adversity [44]. These practitioner reports are used to corroborate and contextualize construction-sector impacts identified in the academic literature, aligning with JBI guidance on the inclusion of grey literature in scoping reviews.

These events challenged the construction industry's reliance on traditional RM frameworks. Conventional probabilistic models and deterministic risk matrices, while useful for frequent, low-impact risks, proved inadequate in managing the unpredictability and severity of BSEs [45,46]. The interconnectedness of modern supply chains amplified cascading risks, complicating recovery and magnifying the impacts of initial disruptions [47,48].

The construction industry's vulnerability to BSEs is exacerbated by its reliance on global supply chains, JIT deliveries, and fragmented project structures. Addressing these challenges requires rethinking supply chain strategies beyond pure efficiency models. Recent literature emphasizes the transition toward JIC strategies, which incorporate inventory buffers, multi-sourcing, and redundancy to enhance resilience; however, evidence suggests that adoption remains context-dependent and varies across project types [17,28,49]. Additional research in construction demonstrated that investing in operational enablers such as supplier partnerships, flexibility in sourcing, and manufacturing technologies contributed to building more resilient and even antifragile supply chains under turbulent conditions [50].

This paper critically examines the impact of BSEs on the construction industry's supply chains, analyzing the weaknesses exposed by recent disruptions and exploring emerging strategies for resilience. Rather than attempting to predict the precise occurrence of such unpredictable disruptions, the review synthesizes how empirical and conceptual studies describe their cascading effects and the organizational responses adopted in construction supply chains, aligning with broader risk perspectives that emphasize learning across unforeseen events [51]. Through a JBI scoping review of 86 peer-reviewed articles and industry reports published between 2000 and 2024, this study synthesizes findings across SCM, RM, lean construction, and BSE management to propose a future-oriented research agenda focused on building adaptive and resilient construction supply chains.

2. Methodology

This study follows the JBI methodology for scoping reviews [52], which provides a structured yet flexible framework to map existing evidence and research gaps on emerging multidisciplinary topics. The JBI approach is particularly suited for exploratory studies where the aim is to identify the breadth and nature of available evidence rather than evaluate interventions. For rare and unforeseen disruptions such as BSEs, risk scholarship stresses that meaningful understanding depends on synthesizing knowledge, experience, and learning across events rather than relying solely on probabilistic prediction [51]. Complementing this view, research on extreme-event management notes that in highly uncertain and complex disruptions, decision-makers must integrate fragmented knowledge, and resilience emerges from aggregating lessons across past crises even when those crises can-

not predict the next one [53]. Accordingly, this review examines how BSEs have impacted construction supply chains and influenced the evolution of RM practices.

The review targeted peer-reviewed publications that addressed themes of SCM, RM, Lean Construction, JIT, resilience, and disruption-mitigation strategies within the construction industry, as well as authoritative industry reports that corroborate or contextualize similar findings and impacts observed in academic studies. Although the inclusion of practitioner reports extends beyond the standard parameters of a JBI review, their use is justified due to the limited volume of BSE-focused academic research specific to construction and the relevance of these sources in validating empirical industry impacts. Following the JBI methodology for scoping reviews [52], the process involved defining broad research questions, establishing inclusion criteria, identifying relevant evidence, screening studies, charting data, and collating findings thematically.

Inclusion criteria emphasized relevance to the construction sector, explicit discussion of BSEs or analogous large-scale disruptions, and availability in English-language sources. Studies published between 2000 and 2024 were included to capture the evolution of global supply chain disruptions, the integration of digital tools, and the development of Lean Construction principles. Authoritative industry reports were also incorporated when they provided construction-specific insights or empirical evidence not yet represented in academic research, thereby supporting triangulation between scholarly and practitioner perspectives.

The literature search drew from databases accessible through Purdue University, including Engineering Village, Scopus, and ProQuest, and was supplemented by manual searches in Google Scholar and citation mapping through Research Rabbit. Search terms combined variations of “Black Swan Events,” “construction supply chain,” “risk management,” “Lean Construction,” “Just-In-Time,” “resilience,” and “disruption.” Boolean combinations and iterative refinement of search strings were employed to ensure comprehensive coverage across disciplinary boundaries.

Study selection followed three iterative stages consistent with the JBI scoping-review process:

1. Abstract screening: Titles and abstracts were manually reviewed to assess relevance to BSE impacts on construction supply chains.
2. Full-text review: Selected articles were examined in full, with particular attention to findings related to risk strategies, supply chain disruptions, Lean and JIT vulnerabilities, resilience-building measures, and anticipatory RM techniques.
3. Backward citation tracing: The reference lists of key papers were reviewed to identify additional foundational or influential studies not captured through keyword searches.

Data charting (defined by JBI as the systematic extraction and recording of key information from included sources to facilitate descriptive and thematic synthesis [52]) and analysis were performed through manual coding and thematic classification, structured around three domains: (1) the disruptive nature of BSEs on construction supply chains, (2) RM and resilience practices adopted or recommended in the literature, and (3) the observed shift from JIT to JIC approaches. This stage corresponds to JBI’s “data extraction and synthesis” phase, intended to organize and summarize recurring patterns in the literature.

As illustrated in Figure 2, the methodology integrates database querying, abstract screening, full-text review, and thematic coding. AI-assisted tools, including Research Rabbit (for citation tracing) and Zotero (for reference management), supported the data-charting process, while editorial tools (ChatGPT 5.2) were used exclusively for grammatical and formatting refinement to enhance readability without influencing the interpretation of findings.

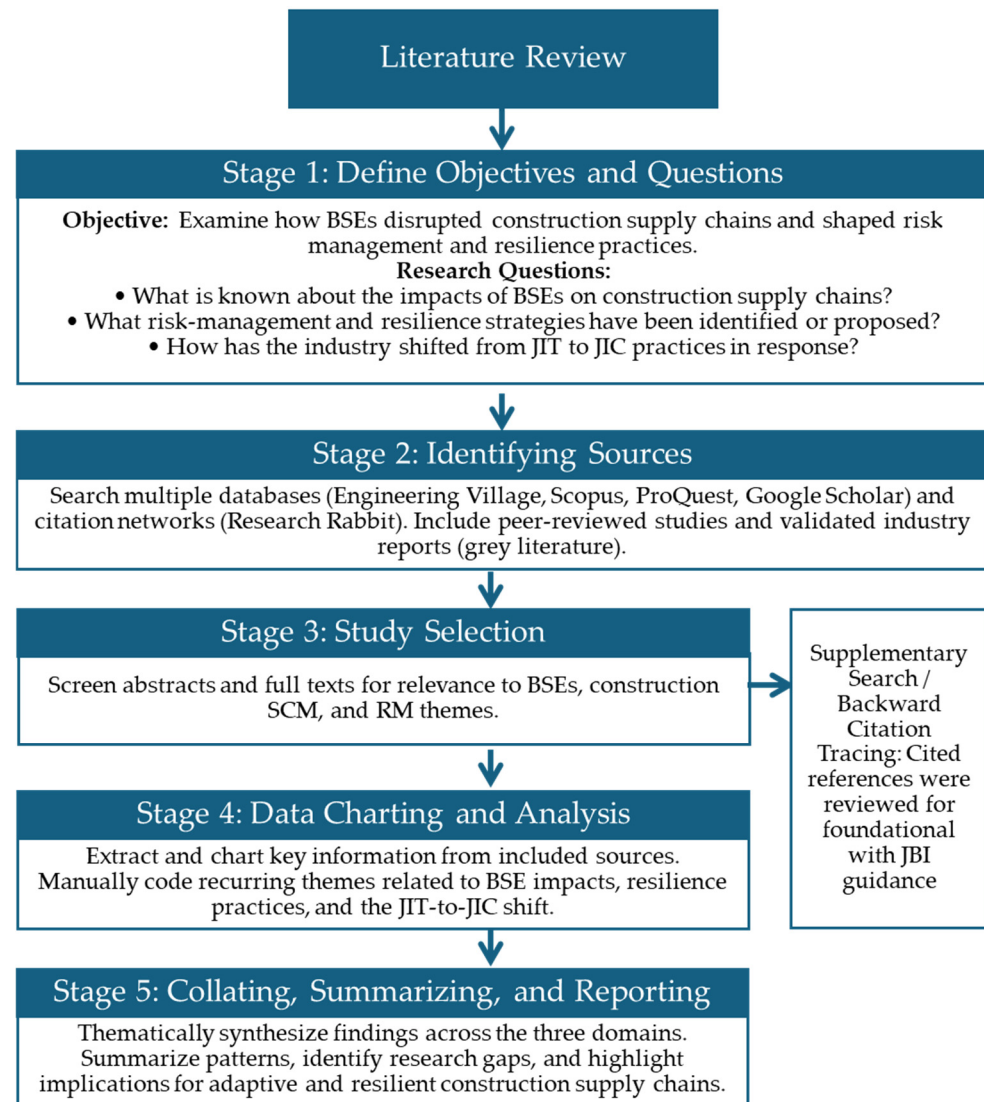


Figure 2. JBI Scoping Review Process for BSE Impacts and Risk Management in Construction Supply Chains.

Limitations: This review did not adopt the PRISMA protocol because its purpose was exploratory rather than evaluative. Nevertheless, the JBI scoping framework provides methodological rigor through transparent search, selection, and synthesis procedures, ensuring replicability and minimizing bias while maintaining the flexibility required for an interdisciplinary topic such as construction supply chain resilience during BSEs.

3. Findings

3.1. Black Swan Events and Their Disruptive Nature

BSEs have fundamentally challenged the assumptions underlying traditional supply chain and risk management strategies in the construction industry. Rather than isolated disruptions, recent BSEs triggered a series of interconnected failures across material procurement, workforce availability, logistics operations, and project financial structures. Understanding the multifaceted impacts of these disruptions requires examining the specific ways in which BSEs have stressed different components of construction supply chains. Drawing from recent global events such as the COVID-19 pandemic, the Suez Canal blockage, and the Russia–Ukraine conflict, the following subsections categorize and synthesize the main disruption dimensions observed in the literature.

3.1.1. Material Shortages

Material shortages emerged as one of the most critical consequences of BSEs affecting construction supply chains. Unlike the traditional expectation that materials would flow seamlessly through JIT systems, the pandemic and subsequent global disruptions revealed how fragile these assumptions were when faced with systemic shocks.

Studies highlighted that COVID-19 brought unprecedented interruptions in the production and availability of essential construction inputs such as steel, cement, glass, and electrical components [40,54]. Severe backlogs arose from manufacturing hub shutdowns in Asia, disrupting both raw material supplies and prefabricated components critical for construction activities [55,56]. As material lead times extended by even months, projects faced cascading schedule delays and cost escalations [57].

The impact of the 2021 Suez Canal blockage compounded existing shortages. Maritime shipment interruptions delayed critical supplies such as piping systems, cladding panels, and mechanical equipment sourced from Europe and Asia, further stressing thin inventories [27,28]. Industry reports noted that supply disruptions for specialized materials, such as piping systems, cladding panels, and mechanical equipment sourced from Asia and Europe, grew particularly acute during this period [58]. Strelzoff et al. (2024) further link supply disruptions to measurable project outcomes, noting that material shortages contributed to patterns of cost and time overruns on critical-infrastructure programs [59].

The Russia–Ukraine conflict introduced a different dimension to material shortages. As global sanctions were imposed and trade routes were disrupted, critical commodities such as steel, aluminum, and neon faced severe supply constraints [32–34]. Neon, an essential input for semiconductor manufacturing, indirectly affected construction technology supply chains, slowing down access to critical equipment for modern building systems [34].

Qualitative impacts compounded quantitative shortages. Contractors, faced with extensive delays, often resorted to substituting original specified materials with available alternatives without full assurance on long-term durability or regulatory compliance [57,60]. Temporary workarounds resulted in hidden costs and rework risks later in project lifecycles. Scholars observed that limited visibility across supply chain tiers contributed to cascading disruptions, as firms with otherwise diversified supplier bases still faced vulnerabilities when second- or third-tier suppliers failed to deliver [15,16].

In response to these widespread shortages, literature increasingly pointed toward strategic stockpiling, dual sourcing, and regional supply diversification as necessary resilience strategies [49]. However, these measures require a fundamental rethinking of JIT efficiency norms traditionally prioritized by the industry.

Overall, material shortages during BSEs demonstrated not only direct procurement disruptions but also the broader systemic interdependencies linking construction supply chains to global economic and geopolitical networks. Evidence from construction projects exposed to catastrophic events illustrates similar patterns, where cascading shortages and logistics breakdowns undermine contractor performance and highlight the need for resilient construction supply chains [61].

3.1.2. Labor Shortages

Labor shortages represented another critical dimension through which BSEs disrupted construction supply chains. Unlike material disruptions, labor constraints impacted project continuity at both operational and managerial levels, compounding delays and creating uncertainty across construction projects globally. COVID-19 restrictions served as a primary catalyst for severe labor shortages during 2020 and 2021. Border closures, health-related site shutdowns, and social distancing mandates significantly reduced the availability of skilled and unskilled labor on construction sites [57,60]. Construction projects in regions reliant on

cross-border workforces, particularly the Middle East, Europe, and North America, faced acute shortages when mobility restrictions were imposed [55,62].

Reduced site staffing slowed construction progress, limited daily output, and delayed project milestones [17]. Studies observed that projects experienced lower labor productivity due to worker absenteeism and pandemic-driven safety protocols, such as reduced crew sizes and staggered shifts, which constrained normal workflows [57].

The pandemic also accelerated labor force attrition, particularly among aging workers, while making construction occupations less attractive to new entrants [43]. Before COVID-19, the construction industry struggled to recruit and retain skilled trades, especially in mechanical, electrical, and plumbing specialties [27]. The Russia–Ukraine conflict contributed indirect labor impacts by displacing millions of workers across Europe, strained local labor markets, and created secondary shortages in regions that absorbed large refugee populations [63].

Construction firms increasingly turned to labor-saving technologies such as modularization, prefabrication, and automation [41]. Skanska [41] identified modularization and prefabrication as emerging strategies to manage labor shortages. Separately, DPR [43] emphasized the adoption of automation and process innovation as part of broader resilience strategies. While these technologies partially mitigated on-site labor needs, they introduced new vulnerabilities, as prefabricated components depended on stable material and logistics supply streams that remained exposed to disruption [54].

Overall, labor shortages during BSEs revealed that human resources in construction are just as critical and vulnerable as physical supply chains. Without adequate contingency planning for workforce disruptions, even projects with available materials struggled to maintain momentum, highlighting labor resilience as a core component of supply chain risk management moving forward.

3.1.3. Logistics Failures

Logistics disruptions during BSEs compounded material and labor shortages, severely straining construction supply chains. Unlike delays caused by material unavailability alone, logistics failures affected transportation, storage, and last-mile delivery of materials and equipment essential for project continuity.

During the COVID-19 pandemic, global freight movement slowed dramatically due to port congestion, limited air cargo capacity, and ground transportation restrictions [18,19]. Construction projects that relied on JIT delivery models suffered schedule impacts even when suppliers held sufficient inventory [13].

The 2021 Suez Canal blockage further illustrated the fragility of global logistics networks. Firms dependent on maritime shipping from Europe and Asia faced cascading project disruptions, highlighting how single-point failures in logistics channels can immobilize entire supply chains [28].

The Russia–Ukraine conflict altered global freight patterns by restricting access to traditional Eastern European transport corridors. Airspace closures and sanctions changed extended delivery timelines and created customs bottlenecks, particularly for construction materials previously sourced through the region [32,34].

Project-level impacts were magnified by a lack of supply chain transparency. Construction firms often lacked real-time information on shipment locations, port backlogs, or customs delays, limiting their ability to mitigate risks proactively [15]. Firms discovered too late that disruptions several tiers upstream had immobilized key materials, further compounding delays [16].

Industry reports suggested several emerging strategies to mitigate logistics vulnerabilities. Firms began investing in alternate supply routes, multi-modal freight options, regional

sourcing hubs, and contingency warehousing to buffer against disruptions [49]. However, these measures often clashed with pre-pandemic cost-minimization priorities, requiring a reorientation of supply chain management philosophies toward resilience rather than pure efficiency.

Ultimately, logistics failures during BSEs exposed transportation and inventory management as critical weak points in construction supply chains. Future strategies must emphasize flexibility, diversification, and improved upstream visibility to enhance the sector's ability to absorb logistics disruptions without jeopardizing project performance.

3.1.4. Financial Volatility

Financial volatility during BSEs augmented supply chain disruptions in construction projects, revealed systemic fragilities in cash flow management, credit access, insurance coverage, and financial risk planning.

COVID-19 triggered sudden project financing delays, renegotiations of existing contracts, and rising insurance costs [40,64]. Contractors faced liquidity shortages as projects were paused or cancelled, creating cash flow constraints that disrupted procurement and payroll processes [55,65]. Financial institutions tightened lending conditions, raising borrowing costs for construction firms [66]. In parallel, insurers introduced pandemic exclusions and raised political risk insurance premiums following the pandemic and subsequent Russia–Ukraine conflict [66].

Shipping cost inflation also compounded financial pressures. The Suez Canal blockage in 2021 delayed shipments and inflated maritime logistics costs, forcing firms to absorb storage penalties, rescheduling fees, and substitution expenses [28]. The Russia–Ukraine conflict further destabilized construction project costs through commodity price surges, especially for steel, aluminum, and energy resources critical to construction [32,33]. Construction firms operating under fixed-price or GMP (guaranteed maximum price) contracts struggled to accommodate rapid material price escalations without eroding project profitability [34].

Currency fluctuations and international financial market instability heightened exposure for firms engaged in cross-border projects. Volatility in currencies such as the euro and ruble increased procurement costs, particularly for imported materials and prefabricated components [67]. Firms without hedging strategies or flexible payment clauses faced unexpected losses due to unfavorable exchange rate movements [64].

Studies indicated that firms better prepared financially exhibited certain common practices. Maintaining liquidity reserves, implementing proactive cash flow monitoring, diversifying funding sources, and renegotiating payment terms with clients and suppliers emerged as key survival strategies [49,65]. Construction companies that adopted flexible procurement clauses, escalation clauses in contracts, and contingency budgeting demonstrated greater resilience against financial shocks [64].

Despite these emerging practices, the literature highlighted that construction industry norms before the pandemic prioritized cost-minimization and lean financial management, leaving minimal buffers for absorbing financial disruptions [49,60]. Moving forward, financial risk management must become a central pillar of supply chain resilience strategies rather than an afterthought to operational optimization.

Overall, BSEs revealed that financial volatility represents a critical threat vector that amplifies material, labor, and logistics disruptions, directly affecting project viability and continuity.

3.2. Supply Chain Risk Management and Resilience Strategies

BSEs have exposed the limitations of traditional RM approaches in the construction industry. Conventional methods, which often rely on probabilistic models and historical data, struggled to anticipate and mitigate the compounding impacts of COVID-19, the

Suez Canal blockage, and the Russia–Ukraine conflict. These events revealed that risk in construction supply chains stems not only from isolated incidents but also from systemic vulnerabilities amplified under extreme uncertainty. As a response, the industry's focus shifted toward resilience strategies emphasizing adaptability, redundancy, and proactive disruption planning. The following subsections examine the evolution from traditional RM frameworks toward resilience-based thinking, culminating in the transition from JIT to JIC strategies.

3.2.1. Traditional Risk Management Approaches

Traditional RM frameworks in construction have historically prioritized identifying, quantifying, and mitigating project-specific risks through structured methods [12,45]. Tools such as risk matrices, Monte Carlo simulations, sensitivity analyses, and deterministic models allowed firms to allocate contingencies and design mitigation strategies based on historical probability patterns [68]. Recent work on construction supply chain risk management reinforced this focus on structured identification and assessment, but also noted fragmented coverage of risks and mitigation strategies along the supply chain [69]. These approaches proved effective for routine risks, such as weather delays or subcontractor defaults, where past experiences offered reliable predictive baselines.

Failure Modes and Effects Analysis (FMEA), a widely used deterministic tool, illustrates additional weaknesses when applied to construction supply chains. While FMEA systematically identifies and prioritizes known risks, its traditional Risk Priority Number (RPN) methodology oversimplifies the complexity of interdependent failures found in construction projects [70].

Composite FMEA was proposed to address these limitations by enhancing the analysis of interactions between multiple failure modes. Instead of evaluating risks independently, COMP-FMEA applies pairwise comparisons to capture how the failure of one element influences others, creating a networked view of risk pathways. To model the evolution of these interconnected failures over time, scholars introduced Markov Chains, a probabilistic technique that simulates transitions between system states based on the likelihood of sequential failures. This dynamic modeling enables better prediction of long-term risk behavior under complex, evolving project conditions [70].

Further, fuzzy logic integrated with Analytic Hierarchy Process (Fuzzy AHP) is used to overcome the subjectivity and uncertainty limitations of traditional FMEA, enhancing risk prioritization and decision-making in construction projects [71]. These approaches help capture the probabilistic and interconnected nature of modern construction supply chains, where single-point failures can cascade across complex networks.

However, BSEs exposed critical limitations in traditional RM systems. Conventional tools operate under the assumption that future risks resemble historical data distributions. BSEs, by contrast, represent unpredictable, high-impact disruptions without historical precedent, invalidating probability-weighted risk forecasts [45,46]. For example, Flage and Aven [72] explained that probabilistic risk assessments, such as those using Monte Carlo simulations, become unreliable when facing completely novel disruptions due to a collapse in the validity of assumed distributions.

Construction RM practices also emphasized contractual risk transfer rather than systemic resilience [73]. Standard industry contracts, such as lump-sum or fixed-price agreements, sought to allocate risks between stakeholders rather than collectively absorb and manage uncertainty. This fragmented strategy failed during BSEs, when systemic supply chain disruptions overwhelmed isolated contractual risk allocations.

Moreover, traditional RM neglected upstream and downstream supply chain risks. Contractors often focused narrowly on project site risks without fully assessing vulnerabili-

ties across material sourcing, logistics, or manufacturing [47]. COVID-19 and subsequent events demonstrated that upstream production delays or logistics failures could cripple project schedules, even when site-level RM appeared robust.

Alternative RM methodologies such as Anticipatory Failure Determination (AFD) and Red Teaming emerged as complements to traditional approaches. AFD emphasizes systematically inventing failure scenarios by deliberately challenging system success assumptions [74]. Unlike conventional FMEA, AFD does not require historical failure data, allowing planners to explore novel disruption paths. The method uses Scenario Structuring Theory to hypothesize systemic breakdowns and map how interdependent components could fail simultaneously, enhancing foresight in highly interconnected systems [74].

Similarly, Red Teaming introduces adversarial simulation to organizational planning. Independent teams probe strategic assumptions, uncover hidden vulnerabilities, and stress-test supply chain robustness against improbable but catastrophic events [75]. Red Teaming counters cognitive biases inherent in traditional expert-driven risk assessments, where confirmation bias and groupthink obscure latent risks [76].

The inclusion of AFD and Red Teaming in construction supply chain RM discussions is critical because they directly address the two main vulnerabilities exposed during BSEs: the inability to foresee emergent failures across interconnected supply networks [47], and the systemic blind spots caused by overconfidence in traditional risk assumptions [76]. Construction supply chains, characterized by complex tiers of subcontractors, material vendors, and international logistics dependencies, cannot rely solely on historic-based probabilistic models. AFD offers a structured method to imagine and plan for unknown failure pathways in upstream and downstream networks, while Red Teaming actively challenges organizational blind spots, exposing weak links before disruptions cascade into major project failures. Without proactive techniques such as AFD and Red Teaming, supply chain RM remains reactive, leaving firms highly vulnerable to future Black Swan scenarios.

Despite these innovations, mainstream adoption of AFD and Red Teaming in the construction sector remains limited. Entrenched reliance on linear, cost-driven risk matrices and historic underestimation of systemic complexity hinder their integration [68]. Moving beyond traditional RM requires deliberate methodological and cultural shifts toward proactive, resilience-oriented frameworks.

Overall, BSEs demonstrated that conventional RM frameworks, while useful for managing predictable operational risks, must evolve to address the complex, interconnected, and unpredictable realities of modern construction supply chains. Evidence from construction projects exposed to catastrophic events illustrates similar patterns, where cascading shortages and logistics breakdowns undermine contractor performance and highlight the need for resilient construction supply chains [61].

3.2.2. Emergence of Resilience Thinking

The severe disruptions triggered by recent BSEs accelerated a shift in RM paradigms within the construction sector. Rather than relying solely on probabilistic models that prioritize efficiency and control, scholars and practitioners increasingly advocate for resilience-oriented frameworks that emphasize adaptability, redundancy, and system-wide robustness under uncertainty [45,77,78].

Resilience in supply chains refers to the capacity to absorb shocks, adapt to unexpected changes, and recover operations without incurring catastrophic failures [79]. Construction supply chains, characterized by multi-tiered networks, global dependencies, and project-specific logistics, have demonstrated pronounced vulnerability to cascading disruptions, making resilience a strategic imperative rather than an operational preference [47].

Resilient supply chains differ fundamentally from efficient ones. Traditional models pursue lean inventory, limited sourcing, and tight scheduling to optimize performance under expected conditions [10]. Resilience thinking, by contrast, accepts volatility as inherent to complex supply systems and prioritizes mechanisms such as inventory buffers, diversified suppliers, modular construction processes, regional warehousing, and scenario planning to maintain operational continuity [77,80].

Emergence of resilience as a guiding principle in construction risk management stems from three critical realizations reinforced by the BSEs:

- Predictive models alone are insufficient: Black Swan disruptions fall outside the boundaries of known risk distributions, making purely anticipatory defenses unreliable and necessitating adaptive capacity [14,45].
- Interconnectedness magnifies disruption propagation: Failures in upstream suppliers, logistics providers, or financing channels rapidly cascade into project-level impacts without warning [47].
- Organizational culture determines recovery speed and robustness: Firms emphasizing flexible decision-making, decentralized authority during crises, and proactive risk intelligence demonstrate faster recovery and reduced vulnerability [19,81].

The literature suggests that resilience must be designed into construction supply chains before disruptions occur, not improvised afterward. Strategies include creating material and labor redundancies, investing in flexible supply contracts, establishing regional supply hubs, and training project teams in adaptive crisis response protocols [28,49].

Although resilience requires upfront costs and sacrifices in operational efficiency, studies highlight that organizations able to maintain project continuity during major disruptions achieve faster recovery, retain client trust, and capitalize on post-crisis market opportunities [79,80]. The next section will examine how the emergence of resilience thinking has catalyzed a transition away from traditional JIT strategies toward JIC models within construction supply chains.

3.2.3. Shift from JIT to JIC Strategies

The COVID-19 pandemic exposed critical vulnerabilities in construction supply chains shaped by JIT practices. Firms that relied on lean logistics, minimal inventory, and single-source procurement encountered immediate delays when suppliers failed to deliver or materials became inaccessible due to transport restrictions [82,83]. As a response, construction firms began shifting toward JIC strategies that prioritized preparedness and resilience over cost minimization [77].

This shift manifested through operational changes including stockpiling of critical materials, diversification of supplier bases, more flexible contract provisions, and investment in upstream supply chain visibility [84,85]. The Table 1 below summarizes the transition:

Table 1. Comparison of JIT and JIC Strategies in Construction Supply Chains Post-BSEs.

Attribute	Pre-Pandemic JIT Model	Post-Pandemic JIC Model	Sources
Inventory Management	Minimal site inventory; tight coordination with suppliers	Increased stockpiling of critical items to prevent shortages	[77,82]
Supplier Strategy	Reliance on few centralized suppliers for efficiency	Diversification and regionalization of supplier networks	[86,87]
Procurement Timing	Materials delivered close to use dates	Early procurement and warehousing to reduce exposure to delays	[83,84]

Table 1. *Cont.*

Attribute	Pre-Pandemic JIT Model	Post-Pandemic JIC Model	Sources
Supply Chain Visibility	Limited oversight beyond direct vendors	Monitoring of multi-tier supply networks for early warning	[87]
Risk Mitigation Focus	Lean-driven, reactive to disruption	Proactive planning, scenario analysis, and supplier risk assessments	[77,86]
Contract Flexibility	Fixed delivery timelines; little allowance for disruption	Escalation clauses and material substitutions to manage volatility	[85,88]
Construction Approach	On-site builds tied to delivery schedules	Off-site fabrication and modular construction to decouple dependencies	[86,89]

Overall, evidence suggests a selective shift toward JIC elements; however, adoption is contingent on project type, material criticality, and contractual context.

Traditional procurement practices under JIT emphasized long-term relationships with a few centralized suppliers to drive cost-efficiency. This structure, while lean, proved vulnerable when upstream disruptions occurred. Raoufi and Fayek [86] identified supplier redundancy and diversification, especially across geographic regions, as key pandemic-era adaptations to increase resilience. Raj et al. [87] further highlighted that many firms reevaluated sourcing strategies and established regional partnerships to counter global logistics volatility.

In procurement timing, the shift became even more apparent. Refs. [83,84] reported that companies began ordering essential materials in advance and holding them in local warehouses. Although this contradicted lean inventory principles and increased storage costs, it ensured continuity in case of transportation delays or shortages.

Regarding supply chain visibility, pre-pandemic models generally lacked transparency beyond Tier 1 suppliers. This limitation prevented early identification of disruptions. Raj et al. [87] documented a post-COVID shift toward multi-tier monitoring tools and systems, allowing firms to map dependencies and respond earlier to emerging issues across the network.

JIT practices underemphasize proactive risk mitigation, often reacting to problems after they emerge. Raoufi and Fayek [86] suggested integrating scenario planning and risk assessments into procurement processes. Christopher [77] similarly argued that resilient supply chains required adaptive structures and the capability to absorb disturbances without collapsing operations.

Contractual rigidity posed another issue. Ogunnusi [88] showed that fixed contract terms often lacked flexibility to accommodate escalating prices or delays. To address this, organizations began adding material substitution clauses, flexible delivery schedules, and escalation mechanisms [85], reflecting a wider adoption of adaptive contracting strategies.

Lastly, the construction approach itself evolved. Traditionally, site-based activities depended on Just-in-Time deliveries, limiting flexibility. Raoufi [85] and Salami [89] reported that companies expanded off-site fabrication and modular construction to reduce on-site dependencies. Modularization not only shortened construction timelines but also shielded projects from upstream delays by decoupling material arrival from on-site progress.

These changes show a hybrid risk-resilient shift rather than a complete abandonment of lean practices. While JIT remains useful under stable conditions, JIC elements, such as early procurement, diversified sourcing, and flexible contracts, form critical complements to achieve resilience under uncertain conditions [77].

4. Comparative Insights from Other Sectors

Construction is not the only sector that faced critical supply chain disruptions from BSEs. Other industries offer instructive lessons on resilience, adaptation, and the evolution

of JIT strategies. Comparative evidence reveals that the transition from JIT to JIC is not unique to construction but part of a broader recalibration of global supply networks under rising uncertainty.

4.1. Manufacturing: Disaster Management and JIT

Toyota's long-standing commitment to JIT emphasized minimal inventory levels and synchronized production flows to optimize efficiency. However, the 2011 Tōhoku earthquake and Fukushima disaster revealed significant vulnerabilities in this model. Sasaki [90] documented how Toyota and other Japanese automakers experienced severe production setbacks not from direct damage, but due to disruptions in lower-tier suppliers. Following Fukushima, Toyota took proactive steps to increase supply chain visibility and resilience without modifying its JIT foundations. Choi [91] explained how Toyota restructured its procurement model by mapping dependencies across Tier 1 to Tier 3 suppliers and stockpiled semiconductors and vital materials, signaling a deliberate shift toward a hybrid supply model that retains lean practices at the factory level while embedding resilience at strategic points in the supply chain. This evolution reflects what Choi et al. describe as "supply chain fit". The company's strategy demonstrates selective adoption of JIC elements, not a wholesale rejection of JIT, underscoring the adaptability of lean principles when integrated with systemic risk awareness.

Other global events have echoed similar supply chain fragilities, reinforcing the shift toward hybridized resilience. De Martini [92] described how Hurricane Florence in 2018 disrupted logistics infrastructure across the southeastern United States, crippling key nodes such as the Ports of Wilmington and Morehead and impeding trucking along Interstate 95. Industries including automotive, pharmaceuticals, and biotech experienced cascading delays. Like the post-Fukushima adjustments seen in Japan, U.S.-based firms have since been pressured to balance cost-efficiency with risk-mitigation strategies, including structural reinforcements and diversified sourcing. The convergence of these cases highlights a growing consensus across sectors: resilience does not require abandoning lean methods but rather enhancing them with adaptive safeguards to withstand systemic shocks.

4.2. Logistics and High-Tech: Looking for Resilience Frameworks

Global logistics and high-tech industries offer tested frameworks for enhancing resilience under disruptive conditions. Sheffi [81] analyzed responses from firms such as Cisco and Intel during major disruptions and found that resilience emerges not from efficiency alone, but from preemptive investment in flexibility, redundancy, and visibility. Resilient organizations maintained decentralized inventories, invested in alternative transportation modes, and cultivated close collaboration with suppliers to ensure rapid response. These capabilities, rather than lean optimization, enabled firms to sustain operations during crises.

Building on this foundation, Pettit [79] developed a formal Supply Chain Resilience Framework, emphasizing the importance of balancing vulnerabilities with capabilities. Vulnerabilities represent internal or external factors that expose a supply chain to risk, while capabilities are attributes that allow an enterprise to anticipate, absorb, or recover from disruption. The framework asserts that supply chain performance improves when firms develop capabilities matched to their specific vulnerabilities, achieving what the authors term "balanced resilience". Capabilities such as flexibility, adaptability, and information sharing reduce exposure to volatility without eroding profitability. However, the authors warn that under-investment in capabilities leads to excessive risk, while over-investment diminishes returns, stressing the need for proportional resilience planning.

Together, these perspectives suggest that supply chain resilience in sectors like logistics and high-tech cannot rely solely on historical risk modeling or JIT efficiency. Instead, re-

silience demands intentional structuring of supply chains to absorb disruption, dynamically reallocate resources, and preserve operational continuity in the face of volatility.

4.3. Global Supply Networks: Post-Pandemic Turn to Buffers and Borders

Brakman [93] argued that the COVID-19 pandemic catalyzed a structural shift in global supply chain management, forcing firms and policymakers to reassess the risks of hyper-globalized, JIT systems. Their analysis emphasized that the pandemic heightened uncertainty to a level beyond calculable risk, prompting a strategic reconsideration of globalization itself. In response, companies began prioritizing “just-in-case” (JIC) approaches, integrating buffers such as increased inventories and diversifying sources of supply, while governments revived border considerations through reshoring and nearshoring policies to improve regional resilience.

Simulation-based insights reinforced this structural pivot. Ivanov [21] demonstrated how epidemic outbreaks create ripple effects that extend unpredictably across supply and demand networks. Ivanov argued that global supply chains designed solely for lean efficiency failed to accommodate compound, multi-layered shocks, particularly when supply availability, logistics mobility, and consumer demand collapsed simultaneously. Complementing this view, Queiroz [94] identified a research agenda that underscored the urgency of supply chain redesign. They argued based on literature that shortened supply routes, enhanced platform coordination, and scenario-based planning emerged as core themes in building post-pandemic resilience.

Translating these concepts into actionable frameworks, Mehrotra [95] illustrated how flexible, decentralized systems can operate under extreme stress. Their ventilator allocation model highlighted the broader applicability of adaptable logistics networks. The study demonstrated that resilience requires more than regional sourcing; it demands governance models that support collaborative allocation and reconfiguration of assets across sectors and geographies. As global supply chains evolve, such models offer blueprints for embedding agility and coordination into future-ready systems.

Building on this foundation, Yang [96] provided empirical evidence that firms with well-developed supply chain risk management capabilities achieved greater operational resilience during and after the pandemic. Their findings showed that real-time data integration, adaptive supplier networks, and proactive risk identification were not only advantageous but essential in volatile global contexts. These capabilities reflect the operational edge required to implement the resilience principles outlined in earlier models, reinforcing the argument that post-pandemic supply chains must combine structural redesign with robust managerial competencies.

Together, this body of work signals a decisive turn in global supply chain thinking. The post-pandemic landscape favors hybrid models that retain the efficiencies of JIT at the operational core while embedding JIC-inspired buffers, visibility, and redundancy into strategic layers. Rather than abandoning globalization, firms are reconfiguring it, aligning networks to absorb shocks while maintaining competitive adaptability.

4.4. Supply Chain Entanglements: Digital Interconnectivity and Pandemic Resilience

The increasing complexity of global supply chains has reinforced the importance of understanding them as dynamic, interconnected systems rather than linear transactional processes. Castells [97] conceptualized this transformation through networks that operate on the principles of real-time data flow, decentralized coordination, and digital interdependence. In this context, the resilience of a supply chain becomes a function of the network's topology and the adaptability of its nodes to absorb and respond to disruption.

Pandemic-era disruptions validated this structural view. Ivanov [98] proposed the concept of the digital supply chain twin, a simulation-based framework for modeling ripple effects and managing disruption risks. By digitally replicating the supply chain network, decision-makers gain visibility into node-level interdependencies and systemic vulnerabilities, enabling real-time adaptation and recovery planning. Parallel developments in logistics reinforce the role of platforms and digital ecosystems as foundational infrastructure for managing network interdependence. Liu [99] observed that the COVID-19 pandemic accelerated the trend of logistics informatization in China. Logistics enterprises deployed integrated information platforms that enabled resource pooling, demand mapping, and agile response, especially during emergency conditions. These platforms transformed logistics into a coordinated, data-driven ecosystem, with shared access to transport capacity, inventory status, and route optimization tools.

Digital mapping and supply chain transparency also emerged as critical tools. Norwood [100] advocated for comprehensive supply chain mapping as a precondition for disruption preparedness. Their findings emphasized that companies unprepared for upstream node failures faced cascading operational breakdowns. Predictive analytics and real-time decision tools extend supply chain mapping into actionable foresight, bridging structural visibility with data-driven responsiveness. Sheng [101] highlighted how big data analytics during the pandemic transformed traditional supply chain models. Decision-making processes shifted toward predictive capabilities, using data patterns to preempt disruptions rather than merely respond.

Sarkis [102] further emphasized that supply chain sustainability and resilience share a foundational requirement: structural integration. Sustainable supply chains must incorporate feedback loops, visibility, and stakeholder collaboration across the entire value network. Resilience cannot emerge from isolated responses but from embedded, structural interdependencies designed to withstand disruption through redundancy, transparency, and real-time coordination.

Together, these studies converge on a critical insight: post-BSE supply chains must be understood as digitally integrated networks characterized by structural interdependencies and adaptive intelligence. Post-pandemic resilience depends on digital interconnectivity, where adaptive intelligence, shared visibility, and coordinated platforms redefine supply chains as integrated ecosystems rather than fragmented links.

In summary, these cross-sector insights reinforce the construction findings in this review: resilience can coexist with lean efficiency when JIC-type buffers, tiered visibility, flexible contracts, and modularization are targeted to specific vulnerabilities. In practice, construction supply chains can adapt these patterns by mapping multi-tier dependencies, pre-positioning critical inventories, and formalizing escalation/substitution clauses to preserve project continuity under BSE conditions.

5. Discussion

Recent BSEs, including the COVID-19 pandemic, the Suez Canal blockage, and the Russia–Ukraine conflict, revealed structural weaknesses in global supply chains and exposed the construction industry's overdependence on JIT procurement. The reviewed literature showed that construction supply chains, historically optimized for cost and efficiency, lack the structural flexibility required to absorb unpredictable and disruptive shocks. Minimal inventories, centralized sourcing, and linear risk planning created compounding vulnerabilities during disruptions.

Supply chain disruptions during BSEs did not manifest as isolated failures but rather as interdependent failures across labor availability, material procurement, logistics coordination, and financial viability. The cascading nature of these disruptions amplified

project delays, introduced cost overruns, and weakened contractual and operational continuity. Traditional RM tools based on probabilistic modeling and historical data failed to account for such volatility due to their inherent limitations in anticipating non-linear, high-impact failures.

Findings illustrate a growing consensus across different authors: construction supply chains must integrate resilience alongside lean efficiency. Strategies such as dual sourcing, inventory buffers, early procurement, modularization, and digital visibility emerged as practical responses to mitigate material and logistics failures.

The shift from JIT to JIC procurement strategies in construction reflects a broader industry-wide recalibration toward resilience. This transition does not abandon lean thinking but reconfigures it. Rather than representing a binary choice between efficiency and redundancy, the emerging hybrid model integrates lean practices at the operational core while embedding targeted JIC elements (such as buffers, redundancy, and risk intelligence) at strategic supply-chain nodes where disruption impact is most severe (e.g., long-lead electrical gear, specialty materials, and chokepoint logistics). Similar trends across sectors such as manufacturing, logistics, and high-tech reinforce this shift, offering transferable models of “fit-for-risk” supply chains.

Despite technological advances as digital twins, multi-tier monitoring, and platform-based freight management which allows real-time visibility and adaptive reconfiguration adopted in different industries, construction remains one of the least digitized sectors, limiting its capacity to operationalize resilience models. Adapting digital infrastructure and cultivating inter-organizational coordination will be necessary to embed resilience at scale. In parallel, risk governance must evolve beyond reactive measures and contractual silos to support proactive, system-level decision-making. In the near term, prioritizing “no-regret” enablers, multi-tier supplier mapping, critical-item dashboards, and standard escalation or substitution clauses can yield tangible resilience gains without requiring full process overhauls.

Future studies should prioritize the development of decision-making frameworks tailored to BSE contexts, where unpredictability renders conventional forecasting ineffective. Research should examine how construction professionals evaluate trade-offs, prioritize options, and execute procurement and supply chain responses under volatile conditions. Methodologies that integrate behavioral insights, scenario-based planning, and adaptive learning will be critical to understanding how resilient decisions emerge in real-time. These studies should also explore how organizational structures, leadership styles, and inter-firm coordination affect the speed and effectiveness of response during cascading disruptions. Such frameworks would support a shift from reactive improvisation to structured adaptability under extreme uncertainty.

Building on this agenda, the authors have conducted subsequent empirical and modeling research that operationalizes the synthesized strategies into a decision-support framework for BSE contexts in construction [103]. The present review, therefore, serves as the conceptual foundation for model design and validation in subsequent empirical studies.

Overall, the discussion reveals that resilience is no longer a strategic option but an operational imperative. Supply chains designed solely for efficiency under stable conditions cannot withstand BSEs. Construction firms that integrate adaptive RM frameworks, diversify sourcing, and invest in digital transparency position themselves to maintain continuity, retain clients, and capitalize on recovery opportunities in volatile environments. Future research should identify and classify the specific resilience strategies currently adopted by industry practitioners. Mapping these real-world adaptations (such as early procurement, dual sourcing, contractual flexibility, and digital visibility) would provide empirical validation of how theoretical frameworks are being translated into practice. Evaluating how

varying degrees of redundancy and flexibility affect project performance, cost, and schedule outcomes will generate actionable evidence to guide large-scale adoption of resilient supply chain strategies in construction.

6. Conclusions

BSEs have fundamentally altered how construction firms must understand, design, and manage their supply chains. The review of 86 peer-reviewed sources revealed that conventional models built for stability and efficiency failed under the stress of recent rare and extreme disruptions. Construction's reliance on lean logistics, centralized sourcing, and fragmented risk management leaves it disproportionately vulnerable when global systems destabilize.

Previous studies addressed disruptions or risk strategies in isolation, often emphasizing on frameworks. This review synthesized the structural effects of BSEs across the construction industry's supply chain and the effects on procurement, labor, logistics, and finance. Findings indicated that shortfalls in inventory, supplier diversity, information transparency, and contract flexibility tend to amplify disruptions rather than contain them. Current risk models fall short not because of technical flaws but due to their misalignment with the systemic interdependencies exposed by BSEs.

The literature did not reject Lean Construction or JIT principles but characterized them as insufficient without complementary resilience measures. Firms that complemented lean methods with adaptive practices demonstrated higher project continuity and quicker recovery. High-performing firms also embedded risk mitigation into procurement and logistics decisions, rather than outsourcing uncertainty to contracts or reacting post-failure.

Comparative insights from manufacturing, logistics, and technology sectors reinforced that resilience operates both as a design principle and a managerial capability. Practices such as digital supply chain mapping, scenario modeling, and proactive supplier collaboration remain underutilized in construction, presenting an opportunity for transformation rather than mere adaptation.

This review does not claim exhaustiveness but offers direction for future research and practice. The construction sector requires cross-disciplinary frameworks that integrate risk analysis, procurement strategy, and digital intelligence. Resilience must be proactively embedded into decision-making processes rather than retrofitted after disruptions occur. Future research should test the proposed resilience measures under controlled scenarios and real-world project settings, evaluating performance trade-offs between lean efficiency and JIC-style buffers.

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Abbreviations

The following abbreviations are used in this manuscript:

AFD	Anticipatory Failure Determination
AHP	Analytic Hierarchy Process
BSE	Black Swan Events
FMEA	Failure Modes and Effects Analysis
JB	Joanna Briggs Institute
JIC	Just-In-Case
JIT	Just-In-Time
RM	Risk management
RPN	Risk Priority Number
SCM	Supply chain management

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