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WITHSTANDING SUPPLY CHAIN VULNERABILITIES IN OFF-SITE CONSTRUCTION LOGISTICS: A NARRATIVE REVIEW AND 3D VISUALISATION

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ABSTRACT

Logistics operations challenges in Off-Site Construction (OSC) trigger Supply Chain Vulnerabilities (SCVs), highlighting the need for a better understanding of appropriate Withstanding Measures (WMs). Existing research often lacks an integrated mechanism to systematically map SCVs and WMs. This limits decision-makers' ability to understand interdependencies and prioritise responses effectively. As a result, there is a need for a visualisation model which also provides structured analysis of the relationships between SCVs and WMs. Therefore, this paper focused on developing a Three-Dimensional (3D) visualisation model to map SCVs and their corresponding WMs. Initially, a narrative literature review approach was employed to identify the SCVs in OSC and their relationships with WMs. A total of 30 papers were s selected through structured screening using predefined inclusion and exclusion criteria. Total of 73 SCVs and 98 WMs both across six thematic categories were identified. Based on the outcome of the literature review, the model was developed using CodeSandbox web development platform. The findings reveal that the integration of Geographic Information Systems (GIS) into Building Information Modelling (BIM) enables the mitigation of the highest number of SCVs. However, 61.64% of the identified SCVs are addressed by only a single WM, indicating limited exploration of WMs in these areas. Therefore, this study offers a novel contribution by developing a 3D visualisation model, addressing a critical gap in both relational mapping and visual decision-support in OSC Supply Chain (SC) logistics.

Keywords: *3D Model; Off-Site Construction; Supply Chain; Withstanding Measures.*

1. INTRODUCTION

The global construction industry, driven by rapid growth and increasing performance expectations, is progressively embracing OSC techniques as an alternative to

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conventional on-site methods (Sanjeepan, 2017). OSC represents a specialised form of industrialised construction in which building components, modules, or prefabricated sections are manufactured and pre-assembled within controlled factory environments (Dunton et al., 2024). Since OSC involves the processes of producing, storing, transporting, and assembling in a tightly synchronised sequence, logistics operations in OSC SCM play a decisive role in enhancing quality and time management, and strengthening overall project performance (Gunawardana & Wedage, 2020). Moreover, Dunton et al. (2024) highlighted that increasing logistics complexity turns small operational issues into larger system-wide risks and expensive delays, thereby increasing the vulnerability of OSC SCs. Similarly, Sanjeepan (2017) argued that supply SCVs in logistics operations, particularly in OSC, need to be properly managed, as they are highly interlinked among multiple stakeholders, and even minor neglect of SCVs, such as logistics availability, can affect overall project success. This makes it of paramount importance to understand SCVs in OSC logistics and their WMs to make the construction project successful.

Ekanayake et al. (2022) identified 37 SCVs in OSC that need to be addressed, and their findings emphasised the need for an action framework that addresses the vulnerabilities identified. A basic framework was developed by Ekanayake et al. (2019) to enhance Supply Chain Resilience (SCR) in industrialised construction by including both potential SCVs and WMs to mitigate these SCVs. Shemov et al. (2020) developed a blockchain-based model to perform construction SC threat analysis. Wang and Zhou (2024) proposed a complex network theory and the cascade failure model for vulnerability analysis in OSC SCs. However, Teymourifar (2026) pointed out that the existing frameworks and models often exhibit conceptual gaps and lack operational clarity, which further constrains their implementation in practice. This is further supported by Lou et al. (2020) who argued that frameworks and traditional models are too abstract and their practical application in real time decision making remains limited due to increasing complexity in information flow. Particularly in OSC SC, traditional linear frameworks and models fail due to dynamic logistics, high interdependencies and requirement for real time collaboration, whereas effective visualisation techniques can represent these aspects more comprehensively. Further, Lou et al. (2022) supported this by articulating that the absence of proper visualisation mechanisms exacerbates these challenges, as complex interrelationships among SC elements cannot be easily understood or communicated.

Visualisation enhances interpretability by transforming complex data into more understandable forms and reducing cognitive burden for decision-makers (Kurasova et al., 2024). However, despite being well-established theoretically by several authors and notwithstanding the growing recognition of complex multidimensional interactions within OSC SCs, the research focusing on visualisation-based analytical models that map SCVs and corresponding WMs remains limited. Similarly, the lack of suitable visualisation tools makes it challenging for practitioners and decision-makers to interpret the complex network of SCVs and WMs within OSC logistics operations. Without effective visualisation, understanding SCV–WM relationships are difficult. To address this gap, this paper focused on developing a 3D visualisation model to map SCV in OSC and their corresponding WMs, thereby enabling improved interpretation of complex interrelationships and supporting effective decision-making.

2. METHODOLOGY

This study is conducted in two phases. Phase I comprised a narrative literature review to identify SCVs and corresponding WMs, while phase II focused on the development of 3D visualisation model. Given the problem-oriented nature of the study, a pragmatic research philosophy which is to select methods based on their practical usefulness in addressing the research problem (Bacon, 2012) was adopted.

2.1 LITERATURE IDENTIFICATION AND DATA EXTRACTION

A narrative literature review approach which is suitable for establishing rationales for future research in areas with limited existing knowledge (Ferrari, 2015) was adopted to identify relevant studies related to OSC SCVs within logistics operations and their corresponding WMs. The literature search was conducted using the Google Scholar database. Keywords were developed under the four primary concept groups:

1. Off-site construction – off-site construction, modular construction, prefabrication
2. Supply chain – construction supply chain, supply chain management
3. Vulnerabilities – vulnerabilities, risk, disruption
4. Withstanding measures – resilience, withstanding measures, withstanding capabilities, mitigation measures, mitigation strategies.

These keywords were combined in different search strings to retrieve relevant publications. The search strings were designed to support a focused synthesis of relevant literature; therefore, the findings represent a structured interpretation of the available literature rather than a comprehensive census of all publications. Following the recommendations of Ferrari (2015), general inclusion and exclusion criteria were considered to maintain the relevance and quality of the selected literature. Priority was given to peer-reviewed journal articles and conference proceedings published in English between 2013 and 2025 to capture recent developments and emerging challenges related to SCR.

Studies that did not sufficiently address SCVs, risks, or WMs were omitted from the review. Similarly, non-academic sources and studies with limited methodological clarity or incomplete information were not considered. The search process initially identified 74 publications, from which the most relevant studies were selected through a review of titles, abstracts, and full texts. Ultimately, 30 papers were retained for detailed analysis and discussion.

From the final selected 30 papers, SCVs and their corresponding WMs were identified. Thematic categories for SCVs and WMs were derived based on recurring patterns, classifications, and terminology reported in the reviewed literature. Several prior studies were used as the basis for identifying common classification structures. For example, Ben-Daya et al. (2019) suggested SCVs related to warehouse, transportation, and inventory management and WMs related to IoT, while Ekanayake et al. (2019) proposed categories such as external environmental, technical, and financial vulnerabilities. Based on these recurring classifications, identified SCVs and WMs were manually grouped into relevant thematic categories according to their characteristics and contextual similarities. Furthermore, vulnerabilities and WMs that could not be directly assigned to the initially identified categories were comparatively analysed and grouped under newly developed relevant categories to maintain consistency in the classification process. Subsequently, each identified SCV and WM was manually assigned to the appropriate thematic category based on its characteristics. In the same manner, relationships between SCVs and WMs were defined by linking each SCV to the WM as reported in the literature, thereby establishing SCV-WM relationship based on documented evidence.

2.2 VISUALISATION MODEL DEVELOPMENT

The visualisation model, developed from scratch, is a React-based 3D force-directed bipartite network defined here as an interactive 3D network in which elements are organised into two distinct groups and automatically positioned using a physics-based layout algorithm. The model was developed using JavaScript (React/JSX) within the CodeSandbox web development environment.

2.2.1 Network Structure

The model consists of a network structure which represents a directed mapping between SCVs and their corresponding WMs (refer Figure 2).

```
{
  id: "V2",
  code: "V2",
  type: "vuln",
  group: "Logistics & Infrastructure Risks",
  name: "Delivery schedule uncertainty / risk of delay",
  degree: 7,
  docsStr: "R7,R9,R26,R28,R19,R1",
```

```
{
  id: "S111",
  code: "S111",
  type: "sol",
  group: "Machine Learning",
  name: "ML-based subsystem simulation modeling",
  degree: 1,
  docsStr: null,
},
```

Figure 1: Java Script code blocks which add the core data set to the model

The network structure consists of two primary node sets: SCV nodes and WM nodes. Node set data which were initially stored in a Microsoft Excel file were transformed into JavaScript (React/JSX) format as depicted in Figure 1 using Microsoft Excel Visual Basic for Applications (VBA).

2.2.2 Node Size and Height

SCV node degree is defined as the number equal to the number of WMs connected to specific SCV. WM node degree is defined as the number equal to the number of SCVs connected to a specific WM (refer Figure 1). Then node geometry (radius and height) is scaled using node degree to visually represent connectivity importance, meaning larger nodes for highly connected SCVs and WMs. For that, the following formulas were used, where *d* denotes the node degree, *Number()* represents a numerical type conversion function, *r* denotes the computed node radius derived from the scaling function, *clamp()* is used to restrict values within predefined bounds to prevent nodes from becoming excessively small or large, *Math.sqrt()* denotes the square root scaling function, and *h* represents the node height.

const d = Number (node.degree || 1) (01)

*return clamp(1 + 6.25 * Math.sqrt(d), 2, 30)* (02)

*const h = clamp(4 + 18 * Math.sqrt(Number(node.degree || 1)), 10, 220)* (03)

Both radius and height dimensions apply square-root scaling to moderate size differences, ensuring that highly connected nodes appear larger and taller, thereby improving visual prominence and interpretability.

3. FINDINGS AND DISCUSSION

3.1 PHASE I – NARRATIVE LITERATURE REVIEW

This study aims to develop a 3D visualisation model to represent SCVs and their corresponding WMs within OSC logistics operations. To achieve the aim, during phase I, 30 selected targeted publications were analysed. 73 SCVs and 98 WMs were identified meanwhile 137 connections between SCVs and their corresponding WMs were examined which were taken directly to phase II to develop the visualisation model. 6 SCV thematic categories and 6 WM thematic categories were identified as described in the previous section. Identified SCVs, their corresponding WMs and groups were depicted in below Table 1. SCV thematic categories include warehouse management and infrastructure risk, financial and market Risks, strategic and organisational risks, information and digital risks, operational and technical risks, and external and environmental risks, while BIM, IoT, blockchain, machine learning, information systems and mathematical models were the 6 thematic categories identified to classify WMs.

3.2 PHASE II – 3D VISUALISATION MODEL

3.2.1 Unique Functionality of the Model

The developed 3D visualisation model and dedicated instructional video is publicly accessible through the following links.

- 3D Visualisation model: https://sc-vmodel3.vercel.app/
- Instructional Video: https://www.youtube.com/watch?v=wlCJsJzlN3c

As outlined in the instructional video, the main functionalities of the model are described in detail below:

- Integrated Legend

The model includes a legend toggle that provides interactive guidance and reference for both SCVs and WMs as depicted in Figure 2.

- Highlighted path

The highlighted path functionality enables users to trace the relationships of a selected SCV or WM. Selecting an SCV or WM from the legend highlights the chosen node, its connected nodes, and their linking edges, as shown in Figure 2.

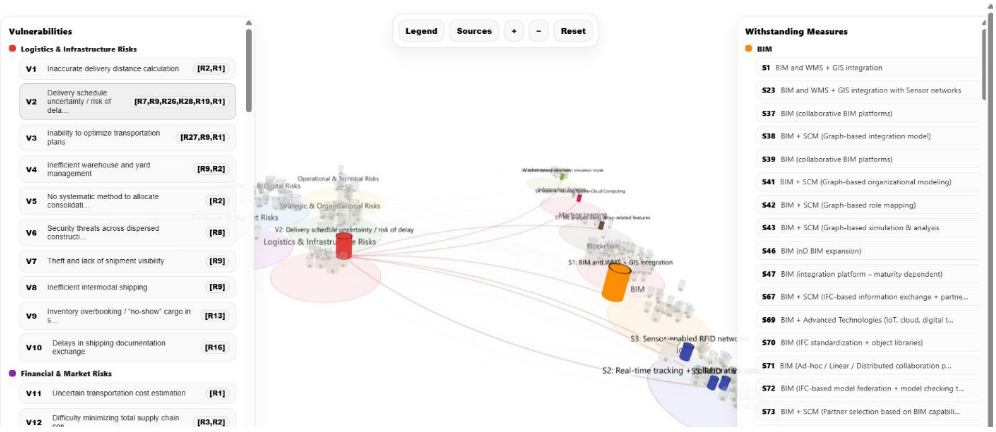

Figure 2: Legend and highlighted path

Table 1: Core data set from narrative literature review - SCV and corresponding WMs

Document	Vulnerability	Withstanding Measure
[R9]	Inefficient warehouse and yard management (VG1)	BIM and WMS + GIS integration (WG1)
		Smart Things (WG4)
[R2]	No systematic method to allocate consolidation centers (VG1)	BIM and WMS + GIS integration (WG1)
[R8]	Security threats across dispersed construction sites/warehouse (VG1)	IoT (Security Monitoring & Identification Systems) (WG4)
[R8]	Security threats across dispersed construction sites/warehouse (VG1)	IoT (Face Detection & Surveillance) (WG4)
[R9]	Inefficient intermodal shipping (VG1)	Smart containers (WG4)
[R13]	Inventory overbooking (VG1)	Blockchain + Smart Contracts (WG3)
[R1]	Uncertain transportation cost estimation (VG2)	BIM and WMS + GIS integration (WG1)
[R2]	Difficulty minimizing total SC cost (VG2)	BIM and WMS + GIS integration with Sensor networks (WG1)
[R13], [R14], [R10]	Presence of intermediaries increasing transaction costs (VG2)	Blockchain (Peer-to-peer transactions) (WG3)
[R13], [R14], [R11]	Presence of intermediaries increasing transaction costs (VG2)	Blockchain + Smart Contracts (WG3)
[R13]	Illegal counterfeiting of products (VG2)	Blockchain + IoT (RFID / QR tracking + ledger) (WG3)
[R16]	Payment disputes in Letters of Credit (LC) (VG2)	Blockchain + Smart Contracts (WG3)
[R16]	Financial and Banking risk (VG2)	Blockchain (Immutable data records) (WG3)
[R17]	inefficient profit distribution (VG2)	Machine Learning (DT, RF, KNN, DNN) (WG2)
[R12]	Supplier and subcontractor payment issues (VG2)	Blockchain + Smart Contracts (WG3)
[R13]	Fraudulent/ forged/delayed documentation in logistics (VG3)	Blockchain (decentralised ledger (WG3)
[R2], [R1]	Difficulty in Supplier Selection (VG3)	BIM and WMS + GIS integration (WG1)
[R13], [R5]	Limited use of advanced technologies for SC integration (VG4)	Blockchain + Smart Contracts (WG3)
[R5]	Lack of process, IT infrastructure standa rdisation (VG4)	BIM (IFC standardisation + object libraries) (WG1)
[R6]	Lack of structured BIM collaboration among multiple firms (VG4)	BIM (Ad-hoc / Linear / Distributed collaboration patterns) (WG1)
[R6]	Redundancy and inefficiency in information exchange (VG4)	BIM (IFC-based model federation + model checking tools) (WG1)
[R6]	Uneven BIM readiness among SC actors (VG4)	BIM + SCM (Partner selection based on BIM measure) (WG1)
[R12], [R13], [R14],	Lack of traceability of materials and components (VG4)	Blockchain (SC traceability + Proof of provenance) (WG3)
		Blockchain + SCO-based Oracles (WG3)
		Blockchain (Immutable ledger + Provenance tracking) (WG3)
		Blockchain + Smart Contracts (WG3)
		Blockchain (Product traceability systems) (WG3)
[R10]	Low digital maturity and information resilience (VG4)	Blockchain-enabled decentralized common data environments (WG3)
[R11]	Lack of reliable historical performance data (VG4)	Blockchain (Immutable transaction history / tracking) (WG3)
[R11]	Poor transparency of transaction records (VG4)	Blockchain (Tamperproof distributed ledger) (WG3)
[R12]	Malicious or noisy sensor data in logistics tracking (VG4)	Blockchain + SCOs + Cross-reference Mechanism (WG3)
[R12]	Inaccurate proof of location for prefabricated components (VG4)	SCOs (GPS Sensors) + Blockchain + Oracle Smart Contracts (WG3)
[R12]	Weak inter-organizational data verification (VG4)	Blockchain + Multi-stakeholder Consensus (PBFT) (WG3)
[R13]	Poor integration between firms' ERP systems (VG4)	Blockchain + ERP integration platform (WG3)
[R12], [R13]	Vulnerability of centralized data systems (VG4)	Blockchain (Decentralized P2P network) (WG3)

Document	Vulnerability	Withstanding Measure	Document	Vulnerability	Withstanding Measure
[R7], [R19], [R17]	Fragmented stakeholder decision-making (VG3)	BIM and WMS + GIS integration (WG1)			Blockchain + Decentralized SCO Oracle Sidechain (WG3)
		Joint IPD governance structure (WG5)			Blockchain (Decentralized ledger architecture) (WG3)
		Machine Learning (DT, RF, KNN, DNN) (WG2)	[R15], [R16]	Security vulnerabilities in intelligent transportation sys. (VG4)	Blockchain (Secure key management frameworks) (WG3)
[R16], [R2]	Lack of coordination between project site and suppliers (VG3)	BIM and WMS + GIS integration (WG1)	[R16]	Lack of transparency across multi-tier SCs (VG4)	Blockchain (Shared digital supply network) (WG3)
		Blockchain (Integrated digital supply network) (WG3)	[R12], [R16]	Security vulnerabilities in centralized ERP systems (VG4)	Blockchain (Decentralized architecture) (WG3)
		BIM (collaborative BIM platforms) (WG1)			Blockchain (Immutable ledger + PBFT consensus) (WG3)
[R5], [R4]	Lack of inter-organizational integration (VG3)	BIM + SCM (Graph-based integration model) (WG1)	[R12], [R3]	Limited quality control and field inspection integration (VG5)	BIM + SCOs + Blockchain (WG1)
		BIM (collaborative BIM platforms) (WG1)	[R8], [R9], [R7]	Lack of Inventory Management (VG5)	IoT inventory alerts + coordinated procurement (WG4)
[R4]	Poor visibility of actor roles and interactions (VG3)	BIM + SCM (Graph-based integration model) (WG1)			IoT (RFID-based Inventory Replenishment & JIT Systems) (WG4)
[R18], [R4]	Mismatch between project duration (VG3)	BIM + SCM (Graph-based integration model) (WG1)			Smart things + multi-agent systems (WG4)
		ML-driven predictive modeling (WG2)	[R9], [R7]	Quality issues (VG5)	Sensor-based monitoring + early stakeholder input (WG4)
		ML-based classification and predictive modeling (WG2)			Time-Temperature Indicator wireless sensors (WG4)
[R5]	Limited flexibility to handle complex SC needs (VG3)	BIM (nD BIM expansion) (WG1)			Sensor-enabled RFID networks (WG4)
[R16], [R5]	Limited outsourcing and third-party logistics integration (VG3)	BIM (integration platform – maturity dependent) (WG1)			Smart packaging (WG4)
[R16], [R5]	Limited outsourcing and third-party logistics integration (VG3)	Blockchain (Distributed Ledger Technology) (WG3)	[R8], [R7]	Lack of real-time monitoring of construction equipment. (VG5)	IoT asset tracking (WG4)
[R8]	Inefficient remote site management (VG3)	IoT (Remote Operations & Monitoring Systems) (WG4)			IoT (Equipment Status Reports & Maintenance Sensors) (WG4)
[R15], [R11], [R13]	Lack of transparency and trust among SC actors (VG3)	Blockchain (Distributed Ledger Technology) (WG3)			IoT (Tracking Systems & Sensors) (WG4)
[R15], [R11], [R14]	among SC actors (VG3)	Blockchain (Immutable ledger + Decentralised validation) (WG3)	[R8]	High maintenance costs due to equipment failure (VG5)	IoT (Predictive Maintenance & Equipment Monitoring) (WG4)
[R15], [R11], [R15]		Blockchain (Tracking + Distributed data sharing) (WG3)	[R9]	Long scanning and recording times (VG5)	RFID tags + Smartphones (WG4)
[R15], [R11], [R16]		Blockchain (permission-based data platform) (WG3)	[R9]	Long processing times in joint ordering (VG5)	Smart things (WG4)
[R15], [R11], F68		Blockchain + Smart Contracts (WG3)			RFID tags + Temperature sensors (WG4)

Document	Vulnerability	Withstanding Measure	Document	Vulnerability	Withstanding Measure
[R15], [R11], F69		Blockchain (Peer-to-peer shipment tracking) (WG3)	[R13]	Product safety failures and difficulty in recalls (VG5)	Blockchain (Immutable shared ledger) (WG3)
[R15], [R11], F70		IoT (Increased SC Visibility Platforms) (WG4)			Blockchain + Smart Contracts (WG3)
[R14]	Opportunistic behaviour and information distortion (VG3)	Blockchain (Transparency + Distributed validation) (WG3)	[R17]	Delays in off-site production (VG5)	Predictive ML models + Data preprocessing (SMOTE, MinMaxScaler) (WG2)
[R17]	Manual or biased resource allocation decisions (VG3)	Data-driven classification models (DT & DNN) (WG2)	[R2], [R1]	Inaccurate delivery distance calculation (VG5)	BIM and WMS + GIS integration (WG1)
[R20]-[R24], [R26]	Lack of risk assessments models (VG3)	AHP–DEMATEL–ISM combined model, ,+ (WG6)	[R9], [R27], [R30], [R19], [R1]	Delivery schedule uncertainty / risk of delay (VG5)	BIM and WMS + GIS integration (WG1)
[R20]-[R24], F90		Fuzzy AHP + Simulation (Simphony.NET) (WG6)	[R9], [R27], [R30], [R19], [R2]		Real-time tracking + collaborative scheduling (IOT + IPD) (WG4)
[R20]-[R24], [R27]		Analytic Hierarchy Process (AHP) (WG6)	[R9], [R27], [R30], [R19], [R3]		Sensor-enabled RFID networks (WG4)
[R20]-[R24], [R28]		Risk Matrix (WG6)	[R9], [R27], [R30], [R19], [R4]		Material Tracking System-Cloud Computing (WG5)
[R20]-[R24], F93		Monte Carlo Simulation (WG6)	[R9], [R27], [R30], [R19], [R5]		RFID + Bar code (WG4)
[R20]-[R24], [R29]	Lack of risk assessments models (VG3)	Failure Mode and Effects Analysis (FMEA) (WG6)	[R9], [R27], [R30], [R19], [R6]	Delivery schedule uncertainty / risk of delay (VG5)	Re-Order Point (ROP) mathematical model (WG6)
[R3], [R1]	Weak coordination between material data and route planning (VG4)	BIM and WMS + GIS integration (WG1)	[R9], [R27], [R30], [R19], [F47]	Delivery schedule uncertainty / risk of delay (VG5)	ML analysis using delay-related features (WG2)
[R13], [R16], [R1]	Manual logistics documentation and reporting (VG4)	BIM and WMS + GIS integration (WG1)	[R28], [R9], [R1]	Inability to optimize transportation plans (VG5)	BIM and WMS + GIS integration (WG1)
		Blockchain + Smart Contracts (WG3)	[R28], [R9], [R1]		Smart things + sensors (WG4)
		Blockchain (Distributed Ledger Technology) (WG3)	[R28]		Probabilistic decision-support methodology (WG6)
[R9], [R2]	Lack of decision-support for logistics optimization (VG4)	BIM and WMS + GIS integration with Sensor networks (WG1)	[R28], [R9], [R1]		Information fusion (WG5)
[R15], [R3]	Poor visibility of material flow across the SC (VG4)	BIM and WMS + GIS integration (WG1)			Cloud computing (WG5)
		Blockchain (Distributed Ledger + Tracking Frameworks) (WG3)	[R9]	Theft and lack of shipment visibility (VG5)	Smart items (WG4)
		Blockchain (Distributed Ledger Technology) (WG3)			Multi-agent systems (WG4)
[R8]		Augmented reality (WG4)			RFID tags (WG4)

Document	Vulnerability	Withstanding Measure	Document	Vulnerability	Withstanding Measure
[R9]		Smart things (WG4)	[R16]	Errors in compliance verification for trade documents (VG5)	Blockchain (Immutable shared ledger) (WG3)
[R15]		Blockchain + Shipment tracking framework (WG3)	[R14], [R1]	Manual sustainability compliance checking (VG6)	BIM and WMS + GIS integration (WG1)
[R9], [R3]	Lack of real-time monitoring of delivery status (VG4)	BIM and WMS + GIS integration (WG1)			Blockchain + Smart Contracts (WG3)
		Smart things (WG4)			Blockchain (Provenance tracking + Certification records) (WG3)
[R13], [R3]	Difficulty identifying supplier locations and availability (VG4)	GIS + Blockchain (Distributed network ledger) (WG3)	[R19], [R8]	Excessive CO_2 emissions (VG6)	IoT (Emission Monitoring & Control Sensors) (WG4)
[R3]	No automated warning system for delays (VG4)	BIM and WMS + GIS integration (WG1)	[R19]		multi-agent simulation (MAS) with deep learning (WG2)
[R6], [R18], [R12]	Fragmented information flows (VG4)	BIM + SCM (WG1)	[R8]	High fuel and power consumption (VG6)	IoT (Power & Fuel Monitoring Systems) (WG4)
[R18], [R4], [R17]		Machine Learning (DT, RF, KNN, DNN) (WG2)	[R13]	Low sustainability transparency in supply networks (VG6)	Blockchain (digital ledger - Provenance) (WG3)
[R13]		Blockchain + Smart Contracts (WG3)	[R14]	Poor carbon footprint tracking (VG6)	Blockchain + IoT integration (SCEnAT 4.0) (WG3)
[R13]	High human errors due to manual processes (VG4)	Blockchain + Smart Contracts (WG3)	[R17]	Risk amplification due to subsystem perturbations (VG6)	ML-based subsystem simulation modeling (WG2)
[R13], [R5]	Limited use of advanced technologies for SC integration (VG4)	BIM + Advanced Technologies (IoT, cloud, digital tools) (WG1)			

SCV Groups - VG1: Warehouse Management and Infrastructure risk, VG2: Financial & Market Risks, VG3: Strategic & Organizational Risks, VG4: Information & Digital Risks, VG5: Operational & Technical Risks, VG6: External & Environmental Risks.

WM Groups – WG1: BIM, WG2: Machine Learning, WG3: Blockchain, WG4: IoT, WG5: Information Systems, WG6: Mathematical Models.

Sources [R1]: (Chen & Nguyen, 2019), [R2]: (Deng et al., 2019), [R3]: (Irizarry et al., 2013), [R4]: (Papadonikolaki et al., 2015), [R5]: (Le et al., 2022), [R6]:(Papadonikolaki et al., 2016), [R7]: (Lotfi & Karakouzian, 2025), [R8]: (Ali et al., 2020), [R9]: (Ben-Daya et al., 2019), [R10]: (Tezel et al., 2020), [R11]: (Qian & Papadonikolaki, 2020), [R12]: (Lu et al., 2021), [R13]: (Cole et al., 2019), [R14]: (Saberi et al., 2019), [R15]: (Queiroz et al., 2019), [R16]: (Gurtu & Johny, 2019), [R17]: (Guo et al., 2025), [R18]: (Wu et al., 2025), [R19]: (Attajer et al., 2025), F81:(Golden et al., 2026), F82: (Qazi et al., 2021), [R20]: (Qiang et al., 2023), [R21]: (Li et al., 2013), [R22]: (Mei, 2023), [R23]: (Starczyk-Kołbyk & Jędras, 2025), [R24]: (Curkovic et al., 2013), [R26]: (Czajkowska & Ingaldi, 2025), [R27]: (Ko et al., 2016), [R28]: (Leontaris et al., 2019), F93: (Ismail, 2021), [R29]: (Rhodes et al., 2022), [R30]: (Panova & Hilletofth, 2018)

- Source identifier

The model includes a sources identifier function linked to the selected SCV. When a SCV is selected from the legend, a Sources button appear and when clicked it displays a table containing the document code according to Table 1, reference details according to the APA 7th style and the DOI.

- Statistical Module

Insights related to statistical measures as described in subsequent Section 3.2.2, can be analysed as shown in Figure 3 using the statistical module integrated in the visualisation model. Figure 3 further illustrates statistical measures related to SCVs only connected to single WM. In addition to that, users can generate customised graphs for each measure. According to the user requirement, the graph can be changed into "counter view" or "percentage view".

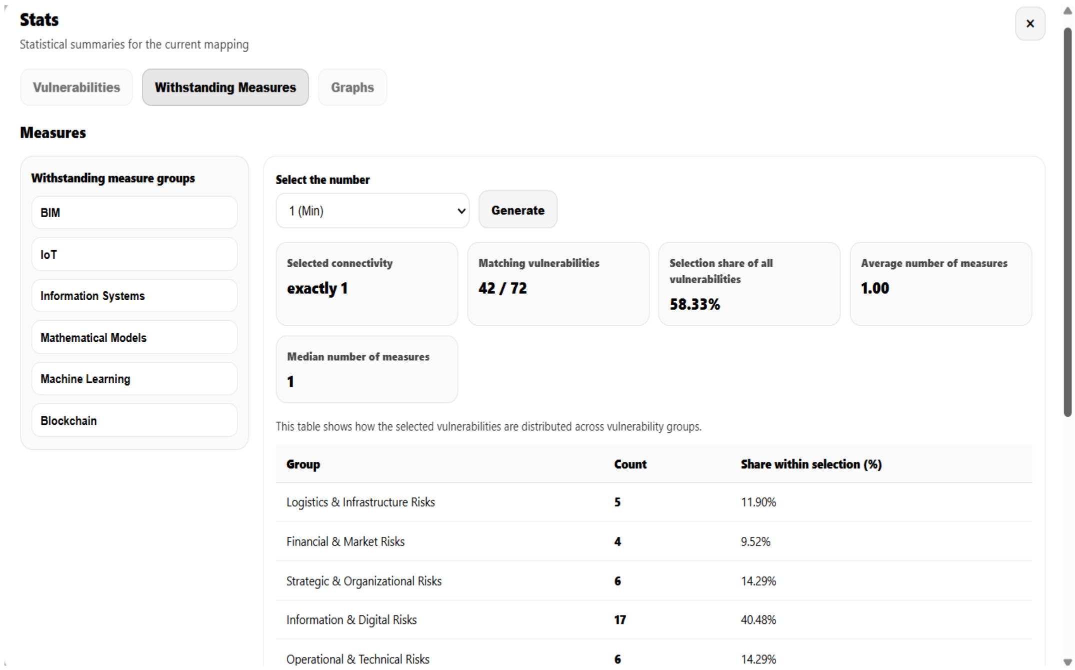

Figure 3: Statistical module

- Graph generation facility

Apart from the graph facility discussed in the previous section, the model provides another graph generation facility within Graph tab in the statistical module. There are two main types of graphs that can be generated using this facility. Type 1 shows each SCV against how many WMs connected them and type 2 displays each WM against how my SCVs are addressed by them.

3.2.2 Insights Derived from the Model

The analysis reveals that a majority of SCVs (61.64%) are associated with only a single WM, indicating that many vulnerabilities in OSC SCs are addressed through isolated and limited WMs. This finding highlights a structural limitation in current mitigation practices, where a lack of diversified strategies may reduce resilience against complex disruptions. Notably, vulnerabilities within the informational and digital risk category show the highest concentration of such one-to-one relationships, suggesting that these areas remain underdeveloped in terms of comprehensive mitigation planning.

In contrast, 35.86% of SCVs are linked to multiple WMs, with vulnerabilities such as delivery schedule uncertainty and transportation optimisation challenges exhibiting the highest number of connections. These findings suggest that critical logistical issues tend to attract more diverse WMs, reflecting their complexity and importance within OSC SCs. This demonstrates that not all SCVs are treated equally, revealing an implicit prioritisation of certain types of vulnerabilities in existing practices.

Furthermore, the model identifies a small number of highly influential WMs, such as GIS integration within BIM, which address a wide range of SCVs across all categories. This highlights the potential of integrated digital solutions to serve as cross-cutting WMs, offering broader systemic benefits compared to isolated interventions. However, the finding that 89.80% of WMs address only a single SCV indicates a prevailing tendency toward fragmented, SCV-specific solutions, particularly within IoT-based approaches.

In relation to prior studies, Wang et al. (2019) also concluded through a literature review that BIM and RFID, which comes under the IoT class, are among the major methodologies adopted in existing research for SC withstanding capabilities. In addition, in line with the finding that 61.64% of the SCVs are addressed by only a single WM, Studer and De Brito Mello. (2021) mentioned that most studies focus on specific areas and reinforced the research gap by highlighting the clear need to present a total solution for SCM in the construction industry. Furthermore, the authors revealed that logistics is the second lowest subject area to be focused on by researchers in SCM domain. Moreover, Papadonikolaki et al. (2015) stated that graph-based approaches have already provided powerful visual and analytic tools for representing complex systems. Therefore, to educate researchers and industry practitioners that OSC logistics remains underexplored, as identified above, the visualisation approach used in this study can be considered highly convincing.

Overall, these findings contribute to knowledge by revealing the imbalance between isolated and integrative WMs in OSC SCs, and by identifying the critical role of multifunctional digital WMs in enhancing SCR.

4. CONCLUSIONS

OSC is rapidly transforming the construction industry due to its distinctive production and delivery characteristics. However, the process from the manufacturing yard to the construction site remains highly dependent on logistics operations, where SCVs can inevitably emerge. For successful project delivery, industry practitioners must develop a comprehensive understanding of these SCVs and the corresponding WMs. Nevertheless, a structured model that enables effective visualisation and analysis of these relationships remains limited. Therefore, this study developed a model to visualise and analyse SCV and their corresponding WMs within the logistics operations of OSC. The developed model facilitates the relationships between SCVs and WMs, provides reference sources for each identified relationship and valuable insights through statistical measures. Model enables researchers to analyse individual SCV and their corresponding WMs behaviour. Furthermore, both academic researchers and industry practitioners can utilise the insights generated to identify the most suitable WMs for addressing specific SCVs. However, the model is constrained by its dependence on a fixed pre identified dataset and simplified representation of relationships, which may not fully reflect the dynamic and evolving nature of construction SCs. Future developments could focus on integrating real-time data sources, enhancing scalability across different project environments, and incorporating advanced analytics such as machine learning to enable predictive and decision-support measures.

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