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## Construction Supply Chain Management in the Fourth Industrial Revolution Era: Prospects and Trends

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### Abstract

Construction supply chain management is undergoing profound transformation in the Fourth Industrial Revolution (4IR) era, driven by digitalization, automation, and intelligent data analytics. This abstract critically examines emerging prospects and prevailing trends shaping construction supply chains as they transition from fragmented, project-based arrangements to integrated, data-driven ecosystems. Central 4IR technologies including Building Information Modelling (BIM), Internet of Things (IoT), artificial intelligence, blockchain, cloud computing, and robotics are enabling real-time visibility, predictive planning, and synchronized collaboration among developers, contractors, suppliers, and regulators. These technologies enhance forecasting accuracy, reduce material waste, and mitigate delays by integrating demand planning, procurement, logistics, on-site operations, and lifecycle asset management on unified digital platforms. In parallel, advanced analytics and digital twins support scenario testing, risk assessment, dynamic rescheduling, and continuous performance benchmarking, thereby strengthening resilience against disruptions such as price volatility, labour shortages, geopolitical shocks, pandemics, and extreme weather events. Sustainability pressures and circular economy principles are further reshaping construction supply chains, encouraging low-carbon procurement, traceability of materials, off-site and modular construction, additive manufacturing, and end-of-life recovery strategies that extend asset value. Social expectations around transparency and ethical sourcing are also accelerating adoption of blockchain-enabled traceability and compliance monitoring across global supplier networks. However, realizing these benefits is constrained by interoperability issues, legacy systems, high initial investment costs, cybersecurity and data privacy risks, skills gaps, and resistance to organizational change. Fragmented standards, contractual misalignment, and weak data governance frameworks also hinder seamless integration across heterogeneous stakeholders and systems. Consequently, firms must adopt strategic roadmaps that align technology adoption with process re-engineering, capacity building, change management, and collaborative governance models that share risks and rewards more equitably. Policy support, industry platforms, and cross-sector partnerships are equally critical for scaling successful pilots into sector-wide transformation and ensuring that small and medium-sized enterprises are not excluded. Overall, the 4IR era offers significant opportunities to enhance efficiency, transparency, resilience, and sustainability in construction supply chain management, but these benefits will only be fully realized when technological innovation is matched with institutional, organizational, and human capability development. Future research should develop robust implementation frameworks, maturity models, and metrics for digitally enabled collaboration performance.

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### 1. Introduction

Construction supply chain management (CSCM) has become a critical determinant of performance in the global construction industry, where projects are characterized by complexity, uncertainty, and tight time–cost constraints. Unlike manufacturing supply chains, construction supply chains are highly fragmented, project-based, and geographically dispersed,

Involving multiple independent stakeholders such as clients, consultants, contractors, subcontractors, suppliers, and regulatory agencies. This fragmentation often results in poor coordination, information asymmetry, delays, material waste, and cost overruns. As construction projects grow in scale and complexity, there is an urgent need to rethink how supply chains are designed, coordinated, and governed to enhance efficiency, transparency, and responsiveness (Bayode, *et al.*, 2019, Keogh & Smallwood, 2021).

The advent of the Fourth Industrial Revolution (4IR) is reshaping how industries create, exchange, and use value through a convergence of digital, physical, and cyber-physical technologies. 4IR is underpinned by innovations such as Building Information Modelling (BIM), the Internet of Things (IoT), artificial intelligence (AI), blockchain, robotics, additive manufacturing, cloud computing, and digital twins. These technologies enable real-time data capture, advanced analytics, and intelligent automation across dispersed actors and processes. In the construction context, they promise to transform conventional linear workflows into integrated, information-rich, and adaptive supply chain networks (Kayembe & Nel, 2019, Matabane, 2019).

Examining the prospects and trends of 4IR-enabled CSCM is therefore both timely and necessary. Construction faces mounting pressures from global competition, client demands for higher quality and faster delivery, rising sustainability and circular economy expectations, and heightened exposure to disruptions such as pandemics, extreme weather, and supply shocks. Understanding how 4IR technologies can improve visibility, coordination, risk management, and sustainability performance across the construction supply chain is essential for guiding strategic investments, policy decisions, and organizational change. At the same time, it is important to identify the barriers, risks, and unintended consequences associated with rapid digital transformation (Kamaruzaman, *et al.*, 2019, Pedron, 2018).

Against this backdrop, the objective of this paper is to explore how 4IR is reshaping construction supply chain management by mapping key technologies, highlighting emerging prospects and trends, and critically assessing the challenges that may hinder their effective adoption. The paper reviews the conceptual foundations of CSCM, outlines the main features of 4IR and its enabling technologies, and analyzes their implications for efficiency, resilience, and sustainability in construction supply chains. It further discusses evolving business models and governance arrangements, examines the barriers and enablers of digital transformation, and concludes by proposing strategic directions and future research avenues to support the successful implementation of 4IR-enabled CSCM (Alade & Windapo, 2019, Vuyiswa & Nischolan, 2019).

## 2. Methodology

The study adopts an integrative systematic literature review design to examine how Fourth Industrial Revolution technologies are reshaping construction supply chain management and to identify emerging prospects, trends, barriers, and enabling conditions. An integrative review is suitable because it allows the combination of conceptual, empirical, and policy-oriented studies from construction, logistics, circular economy, and digital transformation domains into a coherent synthesis. The review is structured around three core analytical lenses derived from the

literature: Industry 4.0/4IR technologies and supply chains (Adebayo *et al.*, 2019; Hofmann & Rüscher, 2017; Koh *et al.*, 2019; Ramli *et al.*, 2018), circular economy and resource efficiency in construction (Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Nasir *et al.*, 2017; Pomponi & Moncaster, 2017; Heshmati, 2017), and resilience/adaptability in the built environment (Béné *et al.*, 2014; Hassler & Kohler, 2014; Carter *et al.*, 2015; Heidrich *et al.*, 2017). These lenses guide the definition of key constructs and the development of the coding framework.

The review universe is defined by peer-reviewed journal articles, conference papers, and authoritative reports published mainly between 2010 and 2024, reflecting the rapid evolution of 4IR concepts and digital technologies. Key databases such as Scopus, Web of Science, ScienceDirect, IEEE Xplore and Google Scholar are searched using Boolean combinations of terms including “construction supply chain management”, “Industry 4.0”, “Fourth Industrial Revolution”, “logistics 4.0”, “digital transformation”, “BIM”, “IoT”, “blockchain”, “digital twin”, “circular economy” and “resilient built environment”. Seminal and recent works identified a priori, such as Adams *et al.* (2017) on circularity in construction, Koh *et al.* (2019) on Industry 4.0 and operations, Hofmann and Rüscher (2017) on logistics 4.0, Lamba and Singh (2017) on big data in supply chains, and Schwab and Davis (2018) on the future of the 4IR, are used for backward and forward snowballing to expand the sample. Additional sectoral studies on digital and AI-enabled supply chains and dashboards (e.g. John & Oyeyemi, 2022; Ogunyankinnu *et al.*, 2022; Francis Onotole *et al.*, 2022; Adeshina, 2021; Wegner *et al.*, 2021, 2022) are purposively included where they offer transferable lessons to construction.

Inclusion criteria require that studies explicitly address at least one of the following: application of 4IR technologies to construction or built-environment supply chains; circular or low-carbon supply chain models in construction and demolition; integration of digital tools (BIM, IoT, AI, blockchain, big data, digital twins) with planning, procurement, logistics or on-site operations; or governance, skills and policy issues related to 4IR in construction (e.g. Keogh & Smallwood, 2021; Alade & Windapo, 2019; Matabane, 2019; Kamaruzaman *et al.*, 2019; Vuyiswa & Nischolan, 2019). Exclusion criteria filter out purely technical materials without supply chain implications, purely macroeconomic 4IR narratives without sectoral focus (unless they provide contextual framing: Li *et al.*, 2017; Morrar *et al.*, 2017; Hirschi, 2018; Penprase, 2018; Akileswaran & Hutchinson, 2019), and studies focused exclusively on end-use consumption without built-environment or supply-chain links (except where they inform circular economy frameworks, such as Winans *et al.*, 2017; Su *et al.*, 2013; Jackson *et al.*, 2014; Walmsley *et al.*, 2019).

The screening process proceeds in two stages. First, titles and abstracts are reviewed against the inclusion criteria, and clearly irrelevant records are excluded. Second, full texts of the remaining studies are assessed to confirm relevance and to ensure that sufficient methodological and contextual information is available for coding. A PRISMA-style log is maintained to document the number of records identified, screened, included, and excluded at each stage, along with principal reasons for exclusion. This enhances transparency and replicability of the review process.

For each included study, data extraction is conducted using a

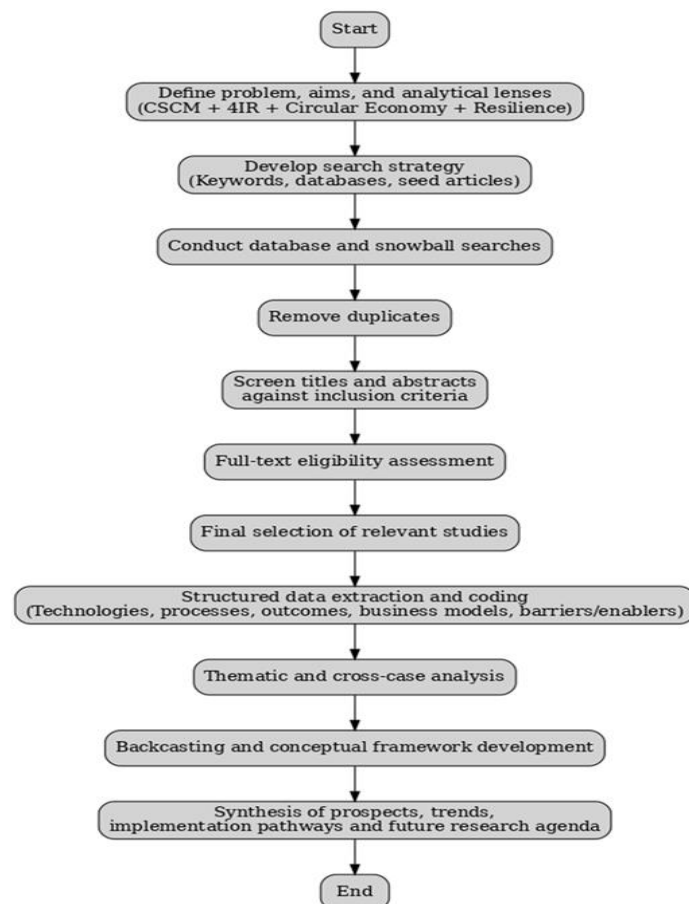
structured template. The template captures bibliographic information; geographical and sectoral context; research design; types of 4IR technologies addressed (e.g. BIM, IoT, AI, big data, blockchain, robotics, digital twins; Adebayo *et al.*, 2019; Hofmann & Rüscher, 2017; Kozma *et al.*, 2019; Lamba & Singh, 2017); supply chain processes covered (planning, design, procurement, production/off-site fabrication, logistics, site assembly, operation and end-of-life); and reported outcomes in terms of efficiency, resilience, and sustainability (Guo *et al.*, 2019; Huang *et al.*, 2018; Ness & Xing, 2017; Sfakianaki, 2015). Further fields record business models (off-site and modular approaches, additive manufacturing, platform-based services; Behera *et al.*, 2014; Gosling *et al.*, 2013; Rios, 2018; Roos, 2014), circular economy strategies (Adams *et al.*, 2017; Leising *et al.*, 2018; Ghisellini *et al.*, 2018; Iacovidou *et al.*, 2017; Velenturf *et al.*, 2019), and identified barriers/enablers (Bayode *et al.*, 2019; Manda & Ben Dhaou, 2019; Ogundipe *et al.*, 2019; Ormazabal *et al.*, 2018).

Qualitative thematic analysis is applied to the extracted data. An initial coding scheme is developed deductively from the analytical lenses and the research questions (efficiency, resilience, sustainability, business models, and governance), and then refined inductively as new patterns emerge from the data. Codes capture, for example, types of digital integration, forms of data governance, configurations of circular supply chains, nature of skill requirements, and observed impacts on cost, time, carbon, and adaptability (Buckman *et al.*, 2014; Gijbers & Lichtenberg, 2014; Pinder *et al.*, 2017; Heidrich *et al.*, 2017). Cross-case comparison is used to identify convergent and divergent findings across geographical regions and organisational contexts, thereby revealing

context-specific and generalisable trends.

To strengthen the forward-looking dimension of the study, the thematic synthesis is complemented with a backcasting-inspired conceptual exercise drawing on circular economy transition frameworks (Heshmati, 2017; Mendoza *et al.*, 2017; Fratini *et al.*, 2019; Moraga *et al.*, 2019) and 4IR transition work (Schwab & Davis, 2018; Li *et al.*, 2017). Desired characteristics of a mature 4IR-enabled, circular and resilient construction supply chain are articulated, and the reviewed evidence is used to map current practices, gaps, and plausible transition pathways. Lessons from adjacent domains healthcare, offshore energy, and agricultural supply chains where AI, dashboards and predictive analytics have been operationalised (Adeshina, 2021; Wegner *et al.*, 2021, 2022; Oyeyemi, 2022; Wegner *et al.*, 2022; Ogundipe *et al.*, 2019) are analysed to identify transferable design principles for data infrastructures, performance dashboards, and risk models in construction.

Throughout the process, attention is given to quality appraisal. Studies are assessed for clarity of objectives, transparency of methods, appropriateness of analytical techniques, and robustness of conclusions. Rather than excluding studies solely on quality scores, appraisal is used to weight evidence in the synthesis and to highlight areas where claims are weak or contested. The final step of the methodology involves integrating the thematic findings into a conceptual framework and a narrative that relate 4IR technologies, circular and resilient supply chain strategies, organisational capabilities, and policy instruments. This framework underpins the proposed implementation and maturity pathways and informs the identification of future research directions.



**Fig 1:** Flowchart of the study methodology

### 3. Conceptual Foundations of Construction Supply Chain Management

Construction supply chain management refers to the systematic planning, coordination, and control of materials, information, finances, and services as they move from original suppliers through various intermediaries to construction sites and ultimately to the end user or asset owner. Unlike supply chains in manufacturing, which often deal with standardized products and repetitive processes, construction supply chains are organized around unique, one-off projects delivered within specific locations and time frames. Each project involves sequences of interdependent activities, from design and procurement to construction, commissioning, and maintenance, that must be synchronized under significant uncertainty (Akileswaran & Hutchinson, 2019, Ramli, Rasul & Affandi, 2018). Construction supply chain management therefore emphasizes the integration of design, planning, procurement, logistics, on-site operations, and downstream asset management, with the aim of delivering projects safely, on time, within budget, and to specified quality and sustainability standards.

A defining characteristic of construction supply chains is their complexity and variability. Projects differ widely in size, type, contractual arrangements, technical requirements, and site conditions, which often leads to bespoke supply chain configurations for each project. The physical nature of construction work, taking place in changing and sometimes remote environments, introduces logistical challenges that are less prominent in factory-based settings. Weather conditions, site access, local regulations, and community constraints all influence how materials, equipment, and labour are mobilised and coordinated (Koh, Orzes & Jia, 2019, Mathur, *et al.*, 2019). Moreover, construction supply chains must accommodate long lead times for critical materials and components, fluctuating demand for trades and subcontractors, and intricate inspection and approval processes that are intertwined with regulatory oversight.

Traditional construction supply chains are highly fragmented and project based. Rather than operating as a stable, long-term network, most supply relationships are formed around specific projects and dissolve shortly after completion. Owners, architects, engineers, main contractors, subcontractors, specialist suppliers, manufacturers, logistics providers, consultants, and regulators are frequently assembled into temporary multi-organisational coalitions. These coalitions are bound together by project-specific contracts that tend to prioritise cost and risk transfer rather than collaboration and shared value creation (Koh, Orzes & Jia, 2019, Morrar, Arman & Mousa, 2017). As a result, incentives are often misaligned, with each party seeking to optimise its own position rather than the performance of the overall supply chain.

The key stakeholders in construction supply chains also tend to have heterogeneous objectives, capabilities, and cultures. Clients may focus on budget control, time to market, and long-term asset performance, while contractors concentrate on delivering within contractual constraints and protecting narrow profit margins. Designers and consultants emphasise compliance with standards and aesthetic or technical quality, whereas suppliers and manufacturers are concerned with production efficiency and market share. Subcontractors and craft workers are deeply engaged in executing site activities but may lack influence over upstream design and planning decisions that shape their performance (Uzoho, 2021).

Regulators, financiers, and insurers add further layers of requirements, approvals, and conditions that must be accommodated within project schedules and cash flows. Coordinating these diverse interests under conventional contracting models is inherently difficult and contributes to inefficiencies. Figure 2 shows Key dimensions of Supply Chain Management presented by Kozma, Varga & Hegedüs, 2019.



**Fig 2:** Key dimensions of Supply Chain Management (Kozma, Varga & Hegedüs, 2019)

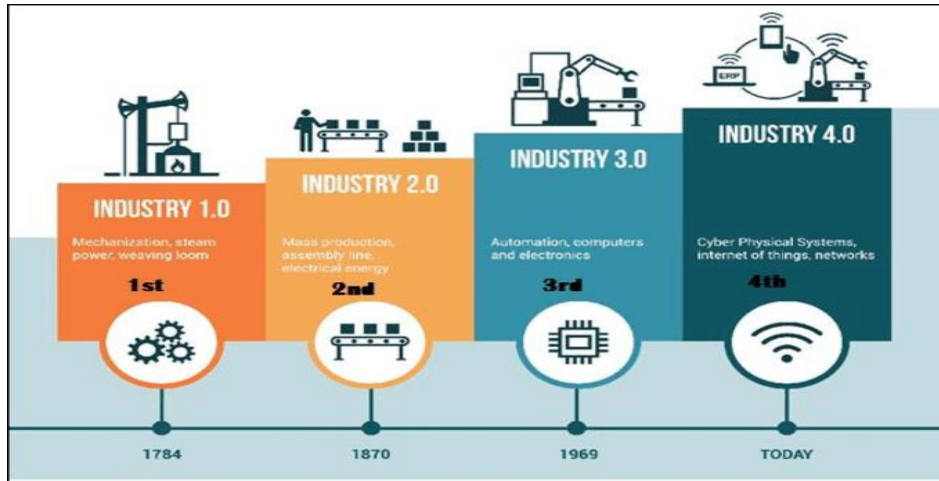
Within this fragmented and project-based environment, typical challenges recur across many construction supply chains. Delays are pervasive, arising from inaccurate demand forecasting, late design information, approvals that take longer than anticipated, supply disruptions, site access problems, and rework caused by errors or design changes. Since many construction activities are sequential and interdependent, disruption at one stage can trigger cascading effects across subsequent tasks and trades. Recovery often requires expensive overtime, resequencing of work, or additional resources, which further complicates coordination and increases risk. The temporary nature of project teams means that lessons learned from one project are frequently lost, leading to repeated mistakes across different projects and organisations (Hofmann & Rüschi, 2017, Lamba & Singh, 2017).

Cost overruns are closely linked to these delays and uncertainties. Budgets in construction projects are often based on incomplete information at early design stages and are subject to change as designs evolve, site conditions are better understood, and stakeholder requirements shift. Contractual claims and variations become common mechanisms for adjusting prices, but they also create adversarial relationships and transactional overheads. Inadequate integration between design, procurement, and construction can lead to suboptimal material specifications, poor constructability, and inefficient resource utilisation. Inventory buffers and contingencies are then used to manage uncertainty, but they lock up working capital and increase overall cost. Weak visibility into upstream supplier performance and market price volatility, especially for key commodities, further exacerbates financial risk (Hirschi, 2018, Li, Hou & Wu, 2017).

Material waste is another persistent issue in construction

supply chains. Poor planning, inaccurate quantity take-offs, design changes, on-site handling problems, and storage constraints frequently result in damaged, excess, or unused materials. Just-in-time delivery is difficult to achieve without reliable data and robust coordination mechanisms, so materials may arrive too early and deteriorate on site or arrive too late and cause work stoppages (Mabo, Swar & Aghili, 2018). Packaging waste, offcuts, demolition debris, and

rework contribute significantly to the environmental footprint of construction projects and add to disposal and compliance costs. Fragmented responsibilities and limited feedback loops between manufacturers, designers, and contractors often prevent systematic learning about the root causes of waste and the design of circular solutions. Figure 3 shows The Four Levels of the Industrial Revolution presented by Adebayo, Chaubey & Numbu, 2019.



**Fig 3:** The Four Levels of the Industrial Revolution (Adebayo, Chaubey & Numbu, 2019)

Information silos underpin many of these challenges. Traditional construction projects rely heavily on paper-based documents, spreadsheets, disconnected software systems, and informal communication channels. Different stakeholders maintain their own records, versions of drawings, schedules, and cost data, which may not be synchronised or accessible to others. This lack of shared, reliable information reduces transparency, undermines trust, and slows decision-making. Requests for information, change orders, and approvals move through slow, manual workflows, creating bottlenecks and increasing the likelihood of errors. Without end-to-end visibility across the supply chain, it is difficult to anticipate risks, evaluate trade-offs, or optimise performance holistically (Penprase, 2018, Syam & Sharma, 2018).

The absence of integrated data also constrains performance measurement and continuous improvement. Many firms track indicators such as cost, time, and safety at the project level, but rarely analyse supply chain performance across multiple projects, suppliers, and regions. Benchmarking is complicated by the uniqueness of projects and the lack of standardised data structures or taxonomies. In this context, improvement initiatives tend to be local and short term, focusing on individual contracts or site practices rather than systemic supply chain redesign. Trust deficits between stakeholders, reinforced by adversarial contracting and blame-oriented cultures, further reduce willingness to share information and collaborate on joint problem solving (Uzoho, 2022).

These conceptual foundations reveal why construction supply chains have historically struggled to match the productivity gains seen in manufacturing and other sectors. The combination of project-based fragmentation, heterogeneous stakeholders, complex site conditions, and entrenched information silos has constrained the potential for integration, standardisation, and learning. At the same time, these characteristics highlight where transformative

opportunities lie (Manda & Ben Dhaou, 2019, Schwab & Davis, 2018). Any approach that can facilitate better integration of information, alignment of incentives, and coordination of activities across organisational boundaries has the potential to significantly improve performance. The Fourth Industrial Revolution introduces a suite of technologies and organisational innovations that directly address many of these structural weaknesses by enabling real-time data sharing, collaborative planning, and digitally supported decision-making across the entire construction supply chain.

#### 4. The Fourth Industrial Revolution and Industry 4.0 Technologies

The Fourth Industrial Revolution (4IR) describes a new phase in industrial development characterised by the fusion of digital, physical, and cyber-physical technologies that enable highly connected, intelligent, and adaptive systems. Building on previous waves of mechanisation, mass production, and automation, 4IR focuses on embedding computation, sensing, and communication capabilities into machines, products, and infrastructure so that they can generate, exchange, and act on data in near real time. Within this broader context, Industry 4.0 refers specifically to the transformation of industrial value chains through smart factories, integrated platforms, and data-driven decision environments that span organisational boundaries (Leising, Quist & Bocken, 2018, Pomponi & Moncaster, 2017).

At the heart of 4IR and Industry 4.0 are concepts such as connectivity, interoperability, and decentralisation. Connectivity refers to the seamless flow of information between devices, platforms, and stakeholders across the value chain. Interoperability concerns the ability of heterogeneous systems and data formats to work together meaningfully, which is essential when multiple organisations and technologies must coordinate. Decentralisation implies that intelligence and decision-making are distributed across the

network, rather than being concentrated in a single central control unit, so that local actors and devices can respond autonomously to changing conditions (Ghisellini, Ripa & Ulgiati, 2018, Heshmati, 2017). Complementing these ideas are principles of real-time data processing, service orientation, modularity, and human-machine collaboration, all of which support more flexible, responsive, and customised production and service delivery.

Several core technologies give tangible form to these concepts in construction supply chains. Building Information Modelling (BIM) provides a shared, object-based digital representation of a built asset and its components across the project life cycle. It functions as a common data environment where geometric, technical, cost, scheduling, and performance information can be integrated. For supply chains, BIM offers the possibility of linking design models directly to procurement, fabrication, logistics, and installation activities, enabling more accurate quantity take-offs, clash detection, constructability analyses, and resource planning. When combined with other digital tools, BIM

becomes a central hub that connects design intent with real-world execution and operations (Winans, Kendall & Deng, 2017, Su, *et al.*, 2013).

The Internet of Things (IoT) extends digital connectivity into the physical environment by embedding sensors, tags, and communication modules into materials, equipment, and infrastructure. In construction supply chains, IoT devices can track the location, condition, and utilisation of materials, components, tools, and plant in real time. Temperature and humidity sensors monitor storage conditions, GPS tags track deliveries, and telematics systems report equipment status and fuel consumption. This granular, continuous stream of data underpins more accurate planning, dynamic routing, predictive maintenance, and safety monitoring. It also supports compliance and quality assurance by providing verifiable records of how and where materials and equipment have been used. Figure 4 shows Supply Chain Management (SCM) in the era of the Fourth Industrial Revolution presented by Paprocki, 2016.

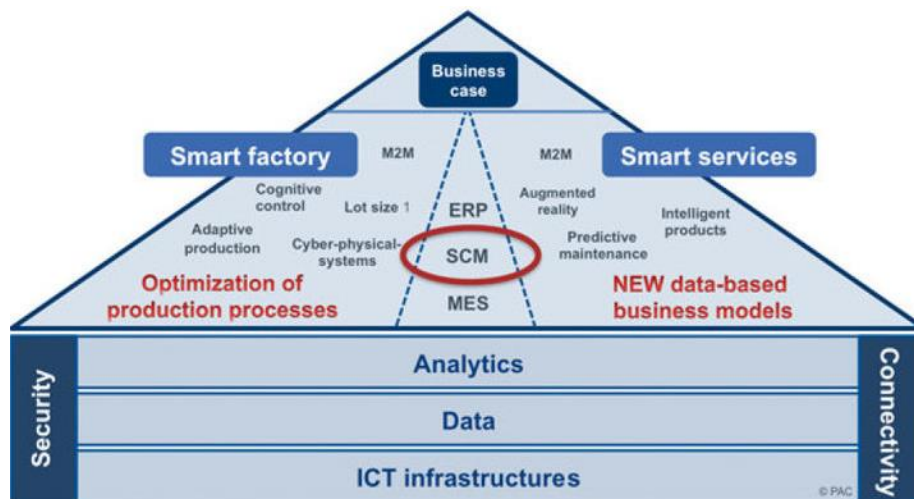


Fig 4: Supply Chain Management (SCM) in the era of the Fourth Industrial Revolution (Paprocki, 2016)

Artificial intelligence (AI) builds on this expanding data landscape by applying machine learning, optimisation, and pattern recognition techniques to support decision-making. Within construction supply chains, AI can improve demand forecasting, identify schedule risks, optimise inventory levels, and recommend alternative suppliers or routing strategies under constraints such as cost, time, and carbon emissions. Computer vision algorithms can analyse images and video from construction sites and warehouses to track progress, detect unsafe behaviours, or assess material stockpiles. As data accumulate across projects, AI systems can learn from historical patterns to suggest more robust plans and identify recurrent bottlenecks that would be difficult for human planners to see (Nasir, *et al.*, 2017, Ormazabal, *et al.*, 2018).

Blockchain technology contributes by providing a secure, distributed ledger where transactions and data exchanges among supply chain participants are recorded in an immutable manner. In construction, blockchain can support provenance tracking of materials, ensuring that products meet specified quality, sustainability, or ethical sourcing criteria. Smart contracts embedded in blockchain networks can automate payment releases when predefined milestones, such as delivery or inspection approval, are digitally verified. This

reduces disputes, shortens payment cycles, and increases trust among stakeholders that often have limited prior collaboration history.

Cloud computing underpins many of these applications by offering scalable, on-demand computing and storage resources that can be accessed from any location. For construction supply chains, cloud platforms host BIM models, IoT data streams, project management tools, and collaboration environments, allowing distributed teams and organisations to work on shared datasets without the need for extensive local infrastructure. Software as a service solutions lower entry barriers for small and medium-sized firms, which can access advanced planning and analytics capabilities without large upfront investment in hardware or bespoke systems (Adams, *et al.*, 2017, Ivanova, *et al.*, 2016).

Robotics and automation technologies are also central to Industry 4.0 and increasingly relevant to construction. In manufacturing-like environments such as off-site prefabrication plants, robots can perform repetitive, high-precision tasks in component fabrication, assembly, and quality control. On construction sites, autonomous or semi-autonomous equipment, such as robotic bricklayers, rebar-tying robots, or drone-based survey systems, can support tasks that are hazardous, labour intensive, or require high

accuracy. For supply chains, robotics enable more reliable and predictable production processes, tighter integration between digital plans and physical execution, and new opportunities for just-in-time delivery of prefabricated elements.

Digital twins integrate many of these technologies into dynamic, virtual replicas of physical assets, processes, or systems. A digital twin of a construction project or facility continuously synchronises with data from BIM models, IoT sensors, and operational systems to reflect the current state of the asset. In a supply chain context, digital twins can simulate alternative logistics strategies, evaluate the impact of delays or disruptions, and test different resource allocation scenarios before decisions are implemented in the real world. They also support lifecycle management by linking design assumptions with actual performance during operation and maintenance, thereby creating feedback loops for continuous improvement (Behera, *et al.*, 2014, Schandl, *et al.*, 2016).

The relevance of 4IR and Industry 4.0 technologies to construction and the wider built environment lies in their potential to address structural weaknesses that have long constrained the sector. Construction supply chains are plagued by fragmentation, information silos, uncertainty, and low productivity growth. By enabling integrated information flows and shared digital representations of projects, 4IR technologies help align the perspectives of designers, contractors, suppliers, and clients. When design models, schedules, cost plans, and logistics data are maintained in interoperable formats, stakeholders can collaborate more effectively, detect conflicts earlier, and coordinate actions across organisational boundaries (Akadiri, Chinyio & Olomolaiye, 2012, Sfakianaki, 2015).

Moreover, the built environment is increasingly expected to deliver not just functional structures but also high standards of sustainability, resilience, and user experience. 4IR technologies support these expectations by enabling better analysis of embodied and operational carbon, promoting circular material flows, and improving the monitoring of building performance over time. IoT-enabled facilities management, combined with AI and digital twins, can optimise energy use, predict equipment failures, and tailor building services to occupant needs. In turn, this performance feedback can be fed back into design and supply chain decisions for future projects (Guo, *et al.*, 2019, Huang, *et al.*, 2018).

Finally, the adoption of 4IR in construction repositions the sector within broader socio-technical and economic systems. As construction firms adopt platform-based business models, off-site manufacturing, and data-driven services, they become part of extended value networks that connect material producers, technology providers, financiers, and end users. This shift opens new opportunities for innovation, productivity gains, and value creation, but also demands new capabilities, governance structures, and collaborative practices. Understanding these technologies and principles is therefore fundamental to analysing the prospects and trends of construction supply chain management in the Fourth Industrial Revolution era.

## 5. Digital Transformation of Construction Supply Chains

Digital transformation is fundamentally reshaping how construction supply chains are conceived, organised, and managed. Traditionally, construction supply chains have been modelled as linear sequences of activities in which

information, materials, and decisions flow in one direction from client to designer, to main contractor, to subcontractors and suppliers, and finally to the site. Each actor typically manages their own portion of the process using fragmented tools and local data, with limited visibility of upstream and downstream activities. In the Fourth Industrial Revolution era, this linear view is giving way to more integrated and data-driven models that treat the supply chain as a dynamic network of interconnected organisations, platforms, and data streams (Hampson, Kraatz & Sanchez, 2014, Roos, 2014). Instead of focusing solely on contractual handovers between discrete stages, digital transformation encourages continuous coordination across the entire project life cycle and across multiple projects.

This shift from linear pipelines to integrated ecosystems is driven by the growing ability to capture, store, process, and analyse large volumes of data generated by design tools, enterprise systems, IoT devices, and field applications. Data no longer resides only in isolated documents or proprietary systems but can be linked through shared identifiers, open standards, and common data environments. BIM models, project schedules, cost databases, supplier catalogues, logistics records, and real-time site data can be federated into overarching digital representations of the supply chain. As a result, planners and managers can move from reactive decision-making based on lagging indicators to proactive, analytics-enabled decision-making informed by near real time information and predictive insights (Heyes, *et al.*, 2018, Williams, *et al.*, 2018).

Real time data sharing is central to this transformation. When sensors track deliveries, equipment utilisation, and site conditions, and when digital platforms capture the status of design approvals, procurement orders, and inspections, stakeholders can access a shared view of current realities rather than relying on outdated reports. Interoperability between systems becomes crucial, since architects, engineers, contractors, and suppliers deploy different software tools tailored to their disciplines. By adopting open data standards, application programming interfaces, and common data environments, organisations can connect these heterogeneous systems so that information flows seamlessly without repeated manual re-entry. Interoperability also supports more flexible supplier relationships, because new partners can plug into established data interfaces without the need to replace their internal systems (Bicket, *et al.*, 2014, Mendoza, *et al.*, 2017).

Platform-based collaboration is another defining feature of digitally transformed construction supply chains. Cloud platforms host BIM models, document repositories, issue trackers, procurement portals, and field management applications that multiple organisations can access according to defined permissions. These platforms function as digital marketplaces and coordination hubs where tenders are issued, bids are evaluated, orders are placed, deliveries are tracked, and progress is reported. They allow the creation of standardised workflows that span organisational boundaries, such as automated routing of requests for information, change orders, or non-conformance reports (Kapsalis, Kyriakopoulos & Aravossis, 2019, Moraga, *et al.*, 2019). By embedding rules and templates into these workflows, platforms help align expectations, reduce administrative overhead, and provide auditable records of who did what and when.

The impacts of digital transformation on planning processes

are profound. With integrated data from design, supply, and site operations, planners can develop more realistic schedules that reflect actual production capacities, supplier lead times, and site constraints. Advanced planning tools can simulate alternative sequences of work, evaluate resource conflicts, and test the impact of different procurement strategies on schedule and cost. The integration of BIM with scheduling tools allows the generation of 4D models that visualise how the project will be built over time, which helps identify clashes, access issues, or congestion before construction begins. As data from ongoing projects is captured and standardised, organisations can refine their planning assumptions based on historical performance rather than relying solely on expert judgement (Velenturf, *et al.*, 2019, Walmsley, *et al.*, 2019).

Procurement processes are also reshaped by digitalisation. Instead of manual, paper-based tendering and fragmented vendor communication, digital platforms support electronic tendering, online bid evaluation, and automated order management. Linking BIM models and cost databases to procurement systems makes it possible to generate material and component requirements directly from design models, reducing errors in quantity take-offs and improving alignment between design intent and purchased products. Supplier catalogues can be integrated into design tools, allowing designers and engineers to select components that are available, compliant, and cost effective early in the process (Iacovidou, *et al.*, 2017, Nambiar, 2019). Data on supplier performance, such as on-time delivery rates, quality non-conformances, and carbon footprint, can be captured systematically and used to inform supplier selection and strategic sourcing decisions.

Logistics operations benefit significantly from real time tracking and analytics. When transportation vehicles, containers, and pallets are equipped with IoT devices, supply chain managers can monitor the whereabouts and condition of materials in transit. This visibility supports dynamic routing, coordination of just in time deliveries, and rapid response to disruptions such as traffic congestion or port delays. Digital tools can optimise loading plans, consolidate deliveries, and schedule time windows for site access to reduce congestion and waiting times. On large projects or in urban environments with tight access constraints, this level of control can dramatically reduce delays and ancillary costs. Integration between logistics data and site schedules allows planners to adjust sequences of work based on actual material availability rather than assumed delivery times (Manniche, *et al.*, 2017, Mylan, Holmes & Paddock, 2016).

Onsite operations are increasingly orchestrated through digital tools that connect field activities with upstream planning and supply chain processes. Mobile applications enable supervisors and workers to access the latest drawings, method statements, and task lists on handheld devices, to record progress, and to report issues immediately. Scanning technologies and RFID tags can verify that materials installed on site match specified products and quantities. Digital checklists and photo documentation support quality control and safety inspections, which can be linked to non-conformance and corrective action workflows on central platforms (Jackson, Lederwasch & Giurco, 2014, Perey, *et al.*, 2018). Drones and laser scanning capture as built conditions that can be compared with BIM models to assess deviations, measure productivity, and update project status. The cumulative impact of these changes is a gradual move

toward more predictable, transparent, and responsive construction supply chains. With digital transformation, decisions concerning planning, procurement, and execution are no longer made in isolation or based on partial information. Instead, they can be informed by shared data, collaborative analysis, and an understanding of whole chain implications. For example, a proposed design change can be evaluated not only in terms of engineering feasibility but also in terms of its impact on supplier lead times, logistics constraints, site workflows, and lifecycle performance. Trade offs between cost, time, risk, and sustainability can be explored using simulation and optimisation tools, rather than relying purely on intuition (Fratini, Georg & Jørgensen, 2019, Linder, 2017).

However, the transition to integrated, data driven models is not automatic. It requires investment in digital infrastructure, process redesign, and change management. Organisations must define data standards, governance mechanisms, and interoperability strategies to ensure that the information they produce is usable by others. Roles and responsibilities may need to be redefined as planners, procurement specialists, logistics coordinators, and site managers increasingly work within shared digital environments. Trust and collaboration must be built among stakeholders who may previously have interacted primarily through formal contracts and adversarial negotiations. When these organisational and cultural conditions are addressed, digital transformation can unlock significant improvements in the planning, procurement, logistics, and onsite operations that underpin construction supply chains and position the sector to take full advantage of the Fourth Industrial Revolution.

## 6. Prospects for Efficiency, Resilience, and Sustainability

The Fourth Industrial Revolution presents a transformative opportunity to achieve efficiency, resilience, and sustainability across construction supply chains. As digital technologies reshape planning, procurement, logistics, and project delivery, the potential for improved forecasting, better resource utilization, and enhanced adaptability to global disruptions becomes increasingly evident. Simultaneously, growing environmental awareness and regulatory pressures are compelling construction firms to adopt low-carbon, circular, and sustainable supply chain practices. Together, these trends mark a paradigm shift toward intelligent, adaptive, and environmentally responsible construction ecosystems (Ness & Xing, 2017, Rios, 2018).

Efficiency in construction supply chain management has historically been undermined by delays, poor coordination, and resource wastage. The integration of Fourth Industrial Revolution technologies such as artificial intelligence (AI), Internet of Things (IoT), Building Information Modelling (BIM), and advanced analytics is now enabling unprecedented levels of predictive accuracy and real-time control. Data-driven forecasting tools powered by AI and machine learning analyse vast datasets from past projects, market conditions, supplier performance, and environmental variables to predict demand fluctuations, material lead times, and potential bottlenecks (Carter, *et al.*, 2015, Pomponi & Moncaster, 2017). This foresight allows project managers to anticipate problems before they arise, aligning procurement and logistics schedules more closely with project progress. For instance, predictive analytics can determine optimal delivery windows, reducing material idling and minimizing on-site congestion. These capabilities foster leaner

operations, lower inventory costs, and reduced rework. Advanced scheduling systems integrated with digital twins and BIM further enhance efficiency. By linking design and construction phases through 4D modelling, project teams can visualize temporal sequences of activities and detect scheduling conflicts early. Simulation-based planning tools evaluate alternative resource allocation strategies, ensuring optimal workforce deployment and equipment usage. Digital coordination reduces idle times, overlaps, and sequencing errors that traditionally cause cascading delays. Moreover, when combined with real-time monitoring via IoT sensors, managers can dynamically update project schedules based on actual site performance, weather conditions, or delivery status, achieving a continuous feedback loop that sustains efficiency from design to handover (Béné, *et al.*, 2014, Buckman, Mayfield & BM Beck, 2014).

Resource utilization also improves significantly in digitally transformed supply chains. Real-time visibility across the value chain allows firms to track material flows, equipment performance, and labour productivity more accurately. IoT-enabled assets generate continuous data on machine health, energy consumption, and operating hours, enabling predictive maintenance that minimizes downtime and extends equipment lifespan. Similarly, smart inventory systems automate replenishment processes and flag obsolete stock, ensuring that resources are deployed efficiently. These capabilities contribute not only to operational savings but also to the reduction of waste and environmental impact (Andrade & Bragança, 2019, Hassler & Kohler, 2014). Through integrated planning, the industry moves closer to a “right-time, right-place, right-quantity” philosophy, replacing reactive crisis management with anticipatory precision.

Resilience has emerged as a central goal of supply chain transformation, especially in the aftermath of global disruptions such as the COVID-19 pandemic, geopolitical instability, and escalating climate risks. The pandemic revealed the vulnerability of traditional construction supply chains to disruptions in logistics, workforce mobility, and raw material availability. In response, 4IR technologies are enabling multi-tier visibility, scenario modelling, and agile response strategies that strengthen resilience. Digital platforms now consolidate data from suppliers, logistics providers, and regulatory authorities, offering a holistic view of supply chain exposure. By simulating potential disruption scenarios such as port closures, material shortages, or extreme weather digital twins and AI models allow managers to assess the ripple effects across the chain and develop contingency plans in advance. These predictive capabilities transform resilience from a reactive stance to a proactive strategy (Gijsbers & Lichtenberg, 2014, Pinder, *et al.*, 2017). Blockchain technology enhances transparency and trust, ensuring that data about transactions, materials, and quality standards remain tamper-proof even in volatile conditions. This transparency builds confidence among stakeholders and facilitates rapid recovery after disruptions by identifying alternative suppliers that meet equivalent compliance criteria. Meanwhile, cloud-based collaboration platforms ensure that project data and communication channels remain accessible even when physical operations are interrupted. During crises, remote project monitoring through drones and IoT devices allows management teams to oversee progress and safety without being physically present on-site. This distributed intelligence reduces the dependency on single points of

failure and supports business continuity (Heidrich, *et al.*, 2017, Schmidt III, *et al.*, 2010).

Resilience is also reinforced through modular and off-site construction strategies supported by 4IR innovations. Prefabrication and additive manufacturing enable production to continue in controlled factory settings, reducing vulnerability to site-specific disruptions. By standardizing components and diversifying supplier networks, firms can mitigate risks associated with regional dependencies and transportation delays. Furthermore, the integration of real-time data analytics helps organisations anticipate supply shocks such as price volatility or raw material scarcity and adjust procurement strategies accordingly. As climate change intensifies extreme weather events, adaptive logistics planning powered by AI ensures that delivery routes and schedules can be dynamically reconfigured, reducing downtime and project interruptions (Eber, 2019, Gosling, *et al.*, 2013).

Sustainability is increasingly recognized as an inseparable pillar of modern construction supply chain management. The industry’s contribution to global carbon emissions, waste generation, and resource depletion has prompted governments and investors to demand greener, more circular approaches. The Fourth Industrial Revolution provides the tools and frameworks necessary to transition toward low-carbon, circular, and resource-efficient supply chains. By integrating life cycle assessment (LCA) tools with BIM and material databases, stakeholders can evaluate the environmental footprint of design and procurement decisions in real time. AI algorithms can recommend low-carbon alternatives for materials or suppliers based on emissions data, price, and availability, ensuring that sustainability is embedded into decision-making rather than treated as an afterthought (Awe, Akpan & Adekoya, 2017, Osabuohien, 2017).

Circular economy principles gain practical traction through digital traceability and material passports. Using blockchain and IoT tracking, materials can be tagged and monitored from extraction to installation and eventual reuse. This traceability enables deconstruction planning, recovery of valuable components, and recycling of materials at the end of a building’s life cycle. Smart contracts can incentivize sustainable behaviour by linking payments to verified performance metrics, such as emissions reductions or waste minimization. These developments mark a departure from linear “take-make-dispose” models toward regenerative construction ecosystems that prioritize resource conservation and carbon neutrality (Akpan, Awe & Idowu, 2019, Ogunidipe, *et al.*, 2019).

Green procurement also benefits from the enhanced data integration made possible by digital transformation. Procurement platforms equipped with sustainability filters allow decision-makers to evaluate suppliers based on environmental performance indicators such as embodied carbon, water usage, and compliance with green standards. Automated analytics can compare bids not only on cost but also on sustainability credentials, fostering a competitive environment that rewards environmentally responsible suppliers. This data-driven transparency aligns procurement practices with broader corporate sustainability goals and global frameworks such as the United Nations Sustainable Development Goals (SDGs). As a result, sustainability shifts from a marketing slogan to a measurable and enforceable criterion within the supply chain (Awe & Akpan, 2017).

The convergence of efficiency, resilience, and sustainability creates powerful synergies. Improved forecasting and resource utilization reduce waste and emissions, directly supporting sustainability goals. Resilient systems, by diversifying sources and optimizing logistics, simultaneously enhance efficiency and lower environmental risk. Conversely, sustainable procurement practices that prioritize local and low-carbon suppliers reduce dependency on global logistics networks, thereby increasing resilience. In this integrated view, the three pillars are not competing objectives but mutually reinforcing outcomes of a digitally enabled transformation (Ajayi & Akanji, 2021, Ejibenam, *et al.*, 2021, Osabuohien, Omotara & Watt, 2021).

Despite these promising prospects, challenges remain. Achieving efficiency through digitalization demands significant investment in data infrastructure, workforce training, and cybersecurity measures. Smaller firms, which form the backbone of many construction supply chains, may struggle with the cost and complexity of adopting advanced technologies. Resilience requires not only technology but also robust governance, contractual flexibility, and cross-sector collaboration. Sustainability ambitions can be undermined by inconsistent standards, data gaps, and lack of accountability mechanisms. Overcoming these barriers will require coordinated policy frameworks, incentive schemes, and industry-wide education efforts to ensure equitable access to 4IR capabilities (Akanji & Ajayi, 2022, Francis Onotole, *et al.*, 2022).

Nevertheless, the trajectory is clear: the Fourth Industrial Revolution is redefining construction supply chain management as a strategic discipline that integrates technological intelligence with environmental and social responsibility. By embracing digital tools for forecasting, data sharing, and lifecycle optimization, construction organisations can achieve higher productivity, greater resilience, and measurable progress toward sustainability goals. The emerging digital ecosystem supports an industry capable of building not only faster and cheaper but also cleaner, safer, and more adaptable to future challenges. This evolution signifies a fundamental shift from reactive project execution to proactive, systems-based management one that aligns economic competitiveness with the urgent global need for sustainable development.

## 7. Emerging Trends and Business Models in 4IR-Enabled CSCM

The Fourth Industrial Revolution (4IR) has catalyzed a wave of transformative trends and business model innovations across construction supply chain management (CSCM). As traditional project delivery models evolve under the influence of digitalization, automation, and data-driven technologies, new approaches such as off-site, modular, and additive manufacturing, blockchain-enabled traceability, smart contracts, and digital twin applications are redefining how value is created and exchanged within the construction ecosystem. These emerging trends mark a decisive shift from fragmented, transactional operations toward integrated, transparent, and performance-oriented supply chain networks (Awe, 2021, Halliday, 2021).

Off-site and modular construction have become among the most significant developments reshaping CSCM. Unlike conventional site-based processes characterized by uncertainty and inefficiency, modular construction relocates much of the production work to controlled factory

environments. Here, precision manufacturing methods, automation, and robotics ensure higher consistency, quality, and safety while minimizing waste. Modules, subassemblies, or entire building components are fabricated, tested, and transported to the site for rapid assembly. This model mirrors lean manufacturing principles and allows parallelization of activities site preparation and module fabrication occur simultaneously thereby shortening project timelines (Adeshina, 2021, Isa, Johnbull & Oveneri, 2021, Wegner, Omine & Vincent, 2021). Digital integration through BIM ensures that design data directly inform manufacturing specifications, linking designers, suppliers, and constructors through a seamless digital thread. Such integration supports just-in-time logistics, reduces on-site congestion, and enhances predictability.

Additive manufacturing, or 3D printing, further extends this paradigm by enabling the direct creation of components from digital models using layer-by-layer fabrication. In construction, additive manufacturing allows for the rapid prototyping of complex geometries, customized designs, and lightweight structures using materials such as concrete, polymers, or composites. The impact on supply chains is profound: production can occur on or near the site, eliminating long-distance transportation and inventory storage. By combining additive manufacturing with robotics and AI-based quality control, construction firms achieve flexibility, cost efficiency, and significant reductions in material waste (Ajayi & Akanji, 2022, John & Oyeyemi, 2022, Osabuohien, 2022). The capacity to print customized structural components also introduces new business opportunities for suppliers who can offer on-demand, locally produced elements instead of mass-produced standard parts. This transition supports a more agile, decentralized, and resilient supply network.

Blockchain technology and smart contracts represent another emerging frontier of transformation in 4IR-enabled CSCM. One of the enduring challenges in construction supply chains has been the lack of transparency and trust among multiple stakeholders. Transactions involving payments, material certifications, inspection approvals, and subcontracting are often slowed by paperwork, disputes, and data inconsistencies. Blockchain addresses these problems by providing a decentralized, tamper-proof ledger that records every transaction in real time. Once data are validated and stored on the blockchain, they cannot be altered without consensus, ensuring accountability and integrity (Akpan, *et al.*, 2017, Oni, *et al.*, 2018). For construction, blockchain enables traceability across the entire project life cycle from raw material sourcing to final installation. Each component can be tagged with a unique digital identity that stores its origin, specifications, and performance history. This level of transparency allows clients, regulators, and contractors to verify compliance with sustainability standards, safety certifications, and ethical sourcing requirements instantly.

Smart contracts, powered by blockchain, automate and enforce agreements without the need for intermediaries. Payment can be triggered automatically when predefined milestones such as material delivery, quality inspection, or project completion are verified through digital records. This automation minimizes delays, reduces administrative overhead, and enhances liquidity for suppliers and subcontractors. It also reduces the potential for disputes, since contract execution is governed by objective data rather than subjective interpretation (Ajayi & Akanji, 2022,

Leonard & Emmanuel, 2022). The introduction of blockchain-based procurement platforms enables smaller suppliers to participate in large projects by demonstrating verified performance histories and compliance credentials, democratizing access to the construction marketplace. Over time, these innovations contribute to an ecosystem of trusted, data-driven relationships that improve financial stability and reduce operational risks.

Parallel to these developments, data-driven decision-making has emerged as a core competency in 4IR-enabled construction supply chains. The volume and variety of data generated across design, procurement, logistics, and field operations are unprecedented. Harnessing this data through advanced analytics, AI, and machine learning allows stakeholders to derive actionable insights for performance optimization. Predictive analytics forecast supply disruptions, cost variations, and schedule deviations, enabling managers to make proactive adjustments. Prescriptive analytics go further by recommending optimal strategies for procurement timing, transportation routing, and workforce allocation (Ogunyankinnu, *et al.*, 2022, Onibokun, *et al.*, 2022). This analytical intelligence transforms supply chain management from reactive problem-solving to continuous, evidence-based improvement.

The evolution of performance metrics is closely tied to this shift. Traditional indicators such as cost, time, and safety are now complemented by advanced metrics measuring carbon footprint, digital maturity, collaboration efficiency, and resilience capacity. Key performance indicators (KPIs) are increasingly monitored in real time through integrated dashboards that aggregate data from multiple digital systems BIM, IoT sensors, enterprise resource planning (ERP), and project management tools. These dashboards provide holistic visibility into supply chain performance, allowing decision-makers to identify inefficiencies and implement corrective measures swiftly. The move toward real-time, multi-dimensional performance monitoring fosters accountability, transparency, and a culture of continuous learning (Ajayi & Akanji, 2022, Isa, 2022).

Digital twin technology represents one of the most transformative applications supporting these new business models. A digital twin is a dynamic virtual replica of a physical asset, process, or system that continuously synchronizes with real-world data. In the context of construction supply chains, digital twins extend beyond the building itself to encompass the entire supply network. They integrate data from design models, supplier databases, logistics platforms, and site sensors to simulate and visualize how materials, equipment, and information flow through the project. By running “what-if” scenarios, managers can test the impact of design changes, schedule adjustments, or supplier delays before implementing them in the real world. This capability enhances decision-making, risk management, and cost optimization (Akomea-Agyin & Asante, 2019, Awe, 2017, Osabuohien, 2019).

Digital twins also support sustainability and lifecycle performance management. For instance, they can track embodied carbon at each stage of material sourcing and transportation, enabling organizations to select greener alternatives. During operation and maintenance, the digital twin can monitor building performance, detect anomalies, and inform predictive maintenance schedules. When integrated with blockchain, it provides an immutable record of asset history, ensuring full traceability from design to

decommissioning. The synergy between digital twins, AI, and IoT thus creates a continuously learning supply chain ecosystem capable of adapting to dynamic project conditions (Ogunyankinnu, *et al.*, 2022, Oyeyemi, 2022).

The business models emerging from these technological trends reflect a shift from ownership-based, siloed structures toward collaborative, platform-oriented ecosystems. Companies are adopting “as-a-service” models in which digital platforms, analytics tools, and equipment are accessed on demand rather than owned outright. For example, equipment-as-a-service allows contractors to pay only for machine hours used, while data-as-a-service platforms offer subscription-based access to real-time analytics and market intelligence. These flexible models reduce capital expenditure, improve cash flow, and promote scalability, especially for small and medium-sized enterprises (SMEs) that might otherwise struggle with high technology adoption costs (Ajayi & Akanji, 2022, Isa, 2022).

Another emerging business model is the integrated project delivery (IPD) framework, which aligns incentives across the supply chain by linking compensation to overall project performance rather than individual outputs. Digital collaboration platforms and blockchain-based smart contracts make it feasible to operationalize IPD at scale, ensuring that rewards are distributed equitably based on measurable outcomes such as schedule adherence, cost savings, and sustainability achievements. This collective accountability encourages cooperation and innovation across traditionally fragmented stakeholders.

Ultimately, the convergence of off-site manufacturing, blockchain-enabled trust mechanisms, data-driven intelligence, and digital twin visualization is redefining the competitive landscape of construction supply chain management. These technologies are not isolated tools but interconnected enablers of new value creation models. The construction industry, once seen as slow to innovate, is now positioned to harness the full potential of digital transformation to deliver smarter, safer, more efficient, and more sustainable built environments. The firms that succeed in this new era will be those that embrace integration, transparency, and agility not merely as technological upgrades but as the foundation of a new digital-first business philosophy that connects every actor in the supply chain through data, collaboration, and shared purpose.

## 8. Challenges, Barriers, and Enablers of 4IR Adoption in CSCM

The diffusion of Fourth Industrial Revolution technologies into construction supply chain management is far from straightforward. While the potential benefits for efficiency, resilience, and sustainability are widely acknowledged, firms encounter a complex mix of technical, organizational, financial, and regulatory barriers that slow or distort adoption. Technically, many construction organisations operate with legacy systems that were never designed for interoperability with BIM platforms, IoT devices, AI tools, or cloud-based collaboration environments. Data are often stored in incompatible formats or isolated in proprietary applications, making integration costly and time consuming. The heterogeneous nature of projects, with each client, contractor, and supplier using different tools, further complicates efforts to establish a common digital backbone across the supply chain. This technical fragmentation limits real time data sharing and undermines the value proposition

of advanced analytics and digital twins.

Organizational structures and cultures pose additional barriers. Construction firms are commonly organised around projects rather than long term process improvement, which means that digital transformation initiatives struggle to secure sustained resources and leadership attention. Hierarchical and siloed decision making can delay the adoption of technologies that require coordination across departments such as design, procurement, logistics, and site management. Traditional contracting practices that emphasise risk transfer and lowest cost bidding do not encourage investment in shared digital platforms or collaborative innovation. In some cases, key supply chain partners are unwilling to adopt new tools unless others do so first, creating a collective action problem where everyone waits for someone else to move (Adeleke & Baidoo, 2022, Oyeyemi, 2022).

Financial constraints are especially acute for small and medium sized enterprises, which dominate many tiers of construction supply chains. The upfront cost of software licenses, hardware upgrades, connectivity, training, and process reengineering can be significant. Return on investment may be uncertain or realised only over multiple projects, while many firms focus on short term survival in competitive markets. Clients do not always reward digital maturity with higher margins or preferential selection, so firms may struggle to justify the investment internally. Access to finance for technology adoption is also uneven, with smaller firms often facing stricter lending conditions and limited awareness of funding schemes (Awe, Akpan & Adekoya, 2017, Osabuohien, 2017).

Regulatory environments can be both a barrier and a driver. On one hand, outdated procurement rules, rigid approval procedures, and inconsistent digital mandates across jurisdictions can slow down the adoption of innovative tools and methods. Requirements for paper based documentation or prescriptive standards that do not account for digital workflows make it harder to capture the full benefits of 4IR technologies. On the other hand, the absence of clear regulations for data sharing, liability in algorithmic decision making, or the use of autonomous equipment may create legal uncertainty that discourages experimentation.

Skills gaps and change resistance represent some of the most critical challenges for 4IR adoption in CSCM. Many professionals in the construction sector were trained in analogue or early digital environments and may lack familiarity with BIM processes, data analytics, or automation technologies. While younger professionals often bring digital skills, they may not occupy decision making positions. The result is a mismatch between the capabilities needed to design and operate integrated digital supply chains and the competencies currently available in many organisations. Training programs are sometimes ad hoc and focused on specific software tools rather than on broader digital literacy and process thinking (Akpan, Awe & Idowu, 2019, Ogundipe, *et al.*, 2019).

Change resistance arises from concerns about job security, loss of professional autonomy, and disruption to established practices. Site managers, estimators, and procurement officers who have developed expertise with traditional methods may perceive digital tools as threats rather than enablers. If early implementations are poorly managed, leading to additional workload or technical glitches, scepticism can harden into active resistance. Contractors and suppliers who see little direct benefit for themselves from

client mandated digital requirements may comply only superficially, undermining the quality and completeness of shared data. Building trust and demonstrating tangible benefits at each level of the supply chain therefore becomes essential (Awe & Akpan, 2017).

Cybersecurity and data governance issues further complicate the adoption landscape. As construction supply chains become more connected, they also become more exposed to cyber risks such as ransomware, data breaches, and sabotage of critical systems. Many firms lack robust cybersecurity policies, dedicated expertise, or incident response plans, and may underestimate their vulnerability. Concerns about protecting commercially sensitive information or personal data can discourage organisations from sharing data on open platforms, which in turn limits the potential for integrated analytics and collaboration. Data governance challenges also include defining ownership and access rights, ensuring data quality and consistency, and agreeing on how data will be used and by whom. Without clear governance frameworks, stakeholders may hesitate to contribute data or rely on shared information for decision making (Akanji & Ajayi, 2022, Francis Onotole, *et al.*, 2022).

Despite these barriers, several enablers can significantly accelerate and support 4IR adoption in construction supply chain management. Policy frameworks are increasingly promoting digital transformation through national strategies, public sector procurement requirements, and funding incentives. Governments that mandate BIM for public works, encourage open data standards, or provide grants and tax incentives for digital innovation create a more favourable environment for investment. Clear regulatory guidance on data protection, cybersecurity, and the use of autonomous systems can reduce uncertainty and foster confidence in new practices (Awe, 2021, Halliday, 2021).

Standards play a crucial role in enabling interoperability and reducing transaction costs. Common data environments and open standards for BIM objects, classification systems, and information exchange allow different software tools and organisations to work together more easily. Standardised processes for information management across the project life cycle help clarify roles and responsibilities, making collaboration more predictable. International and industry standards relating to quality management, environmental performance, and health and safety can be integrated into digital workflows so that compliance is monitored automatically.

Capacity building is another key enabler. Structured training programs, professional development curricula, and academic courses that integrate digital skills with construction management knowledge are needed to close the skills gap. Cross functional training within organisations can help professionals understand how their work fits within the broader digital supply chain. Pilot projects that provide hands on experience with 4IR technologies can build confidence and generate internal champions who advocate for wider adoption. Partnerships between industry, academia, and technology providers can accelerate learning and reduce duplication of effort.

Ensuring that small and medium sized enterprises are included in the digital transition is essential for achieving system wide benefits. Initiatives such as shared digital platforms, subsidised training, and collaborative innovation networks can lower entry barriers for SMEs. Large clients and main contractors can support their supply chains by

providing access to tools, templates, and technical assistance, and by structuring contracts that share the benefits of digital efficiencies rather than imposing unfunded mandates. Industry associations can play a convening role by disseminating good practice, developing sector specific guidelines, and lobbying for supportive policies (Adeshina, 2021, Isa, Johnbull & Oveneri, 2021, Wegner, Omine & Vincent, 2021).

Ultimately, overcoming the challenges and leveraging the enablers of 4IR adoption in CSCM requires a holistic approach that aligns technology, people, processes, and institutions. Technical solutions alone are insufficient if organisational cultures, financial incentives, and regulatory frameworks remain misaligned. Equally, policy and standards will remain abstract if firms lack the skills and confidence to implement them in practice. When these elements are brought into alignment, digital technologies can move from pilot experiments to routine, value generating components of construction supply chain management, positioning the sector to deliver projects that are more efficient, resilient, and sustainable (Ajayi & Akanji, 2022, John & Oyeyemi, 2022, Osabuohien, 2022).

## 9. Conclusion and Future Research Directions

Construction supply chain management in the Fourth Industrial Revolution era stands at a decisive turning point. The synthesis of concepts and trends explored across the preceding sections illustrates a clear trajectory from fragmented, paper driven, and reactive project arrangements toward integrated, data intensive, and collaborative ecosystems. Core 4IR technologies such as BIM, IoT, AI, blockchain, cloud computing, robotics, and digital twins are reshaping how information, materials, and decisions flow across the life cycle of built assets. They enable improved forecasting, more reliable scheduling, leaner resource utilisation, and enhanced visibility across multiple tiers of suppliers and contractors. At the same time, emerging practices such as off site and modular construction, additive manufacturing, blockchain enabled traceability, and platform based collaboration are reconfiguring traditional business models and redefining what “good performance” means in construction supply chains.

The key prospects in 4IR era CSCM revolve around efficiency, resilience, and sustainability as mutually reinforcing outcomes. Efficiency gains arise from predictive analytics, integrated planning, and real time monitoring that reduce delays, rework, and material waste. Resilience is strengthened by multi tier visibility, scenario modelling, and the ability to reroute, reschedule, or reconfigure supply networks in response to pandemics, market shocks, and climate related disruptions. Sustainability is advanced through digital tools that support low carbon design choices, circular material flows, and evidence based green procurement. Together, these trends point toward construction supply chains that are not only faster and more cost effective but also more adaptive and better aligned with broader environmental and social goals.

For industry practitioners, the strategic implications are profound. Contractors, consultants, suppliers, and logistics providers can no longer treat digital tools as optional add ons or isolated IT projects. Instead, 4IR adoption must be approached as a core strategic capability that shapes competitive advantage, risk exposure, and value creation. This demands investment in interoperable data

infrastructures, skills development, and new forms of collaboration that transcend project boundaries. Firms that succeed will be those that move from viewing each project as a stand alone endeavour to managing portfolios of projects through shared platforms, standardised processes, and reusable data assets. They will cultivate cross functional teams that understand both construction practice and digital technologies and will embed continuous learning into their operations through feedback from digital twins and analytics. Policymakers also have a critical role in shaping the trajectory of 4IR enabled CSCM. Public sector clients are in a position to set expectations for digital delivery, open standards, and sustainability outcomes through procurement requirements and regulatory reforms. Clear policy frameworks can reduce uncertainty around issues such as data sharing, liability in automated decision making, cybersecurity obligations, and the use of autonomous equipment. Incentive schemes, grants, and tax credits can help de risk investment in digital transformation, particularly for small and medium sized enterprises that form the backbone of many supply chains. At the same time, governments must ensure that digital mandates are accompanied by practical guidance, training support, and realistic transition timelines so that requirements do not entrench inequalities between large and small firms.

To translate technological potential into consistent performance, there is a need for robust implementation frameworks and maturity models tailored to construction supply chains. Such frameworks should recognise that digital transformation progresses in stages, from basic digitisation of documents and processes to full integration of data across organisations and, ultimately, to predictive and autonomous decision environments. Maturity models can help organisations benchmark their current capabilities in areas such as data governance, interoperability, analytics, collaboration, and sustainability and identify targeted improvement pathways. Effective frameworks will combine technical dimensions with organisational and cultural factors, addressing leadership commitment, incentive structures, contractual models, and change management strategies. They should also offer practical guidance on aligning digital initiatives with lean and quality management principles, rather than treating them as separate agendas.

Future research has a vital role to play in deepening understanding and guiding practice. There is a pressing need for empirical studies that quantify the impacts of 4IR technologies and business models on cost, time, quality, safety, resilience, and environmental performance across diverse project types and regional contexts. Longitudinal research tracking digital transformation over multiple projects and economic cycles would provide insights into learning curves, path dependencies, and the conditions under which benefits are sustained. More conceptual work is required to refine theories of supply chain integration, governance, and collaboration under highly digital and platform based arrangements, including the implications for power relations, risk allocation, and value sharing among stakeholders.

Priority research areas include the experiences and challenges of SMEs in adopting 4IR tools and participating in digital platforms, the integration of circular economy metrics into performance management, and the human and organisational aspects of digital change, including trust, professional identity, and worker wellbeing. The interactions between 4IR

technologies and emerging regulatory regimes on data protection, carbon reporting, and sustainable finance also deserve careful examination. In addition, the potential unintended consequences of automation, algorithmic decision making, and data concentration should be critically explored, to ensure that digital transformation contributes to inclusive and equitable industry development.

Overall, construction supply chain management in the Fourth Industrial Revolution era presents both remarkable opportunities and substantial challenges. The sector is moving toward more connected, intelligent, and sustainable modes of operation, but progress will depend on the ability of practitioners, policymakers, and researchers to align technological innovation with institutional reform, organisational capability building, and thoughtful governance. By developing coherent implementation frameworks, context sensitive maturity models, and a strong empirical evidence base, the construction community can move beyond isolated pilots and fragmented adoption toward systemic transformation, positioning construction supply chains to meet the economic, environmental, and societal demands of the decades ahead.

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