The Impact of Industry 5.0 Technologies on Supply Chain Integration in the Construction Sector: A Systematic Review

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3 ABSTRACT

The construction industry, as the backbone of modern infrastructure, plays a pivotal role in global growth. However, it continues to grapple with inefficiencies, fragmented supply chains, and persistent coordination challenges. As projects grow increasingly complex and demands intensify, these long-standing issues pose greater risks to project success. In response, Industry 5.0 technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Blockchain—are emerging as transformative forces, with the potential to revolutionize supply chain management in construction. This study examines how these advanced technologies can reshape traditional construction supply chains into integrated, efficient, and resilient systems. Through a systematic review of the existing literature, the research reveals that Industry 5.0 technologies enable real-time data sharing, predictive analytics, and enhanced transparency, which significantly reduce delays and improve project outcomes. Nevertheless, the adoption of these technologies presents considerable challenges. High implementation costs, the absence of standardized protocols, cybersecurity concerns, and entrenched resistance to change remain formidable obstacles. The findings emphasize the need for strategic collaboration, robust frameworks, and substantial investments in both technology and human capital to overcome these barriers and ensure the long-term success of the sector.

4 DECLARATION

I hereby declare that the work presented in this dissertation is my own, original work, except where otherwise clearly referenced and acknowledged.

I further declare that no portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification at this or any other university or institute of learning.

5 Intellectual Property Statement

6 INTRODUCTION

The construction sector, a vital pillar of global economic development and infrastructure growth, continues to play a central role in shaping our built environment (Barbosa et al., 2017). However, despite its critical importance, the industry faces enduring challenges, including fragmented supply chains, operational inefficiencies, and poor coordination (Vrijhoef & Koskela, 2000). These issues frequently result in costly delays, budget overruns, and compromised project outcomes, undermining the sector's overall effectiveness (Gbadamosi et al., 2022). As construction projects become increasingly complex, the need for innovative solutions to streamline operations and enhance supply chain integration has never been more urgent (Oesterreich & Teuteberg, 2016).

Amidst these ongoing challenges, the advent of Industry 5.0 technologies offers a promising pathway to transformation. Specifically, the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Blockchain are at the forefront of this technological revolution (See appendix 12.2 for detailed information about these technologies), poised to redefine how supply chains are managed within the construction industry (Ribeirinho et al., 2020; Gbadamosi et al., 2022). Unlike Industry 4.0, which emphasized automation and digitalization, Industry 5.0 introduces a human-centric approach that leverages advanced technologies to create seamless collaboration between human expertise and machine capabilities (Demir et al., 2020). In an industry where effective supply chain management is critical, these technologies present an opportunity to drive substantial improvements by enabling real-time data sharing, predictive analytics, and enhanced transparency (Oesterreich & Teuteberg, 2016).

Despite the recognized potential of these technologies, their application within the construction sector remains underexplored. Much of the existing research has focused on theoretical benefits or their implementation in other industries, often neglecting the unique complexities that characterize construction (Gbadamosi et al., 2022; Oke & Aigbavboa, 2017). This gap in the literature underscores the need for empirical studies that investigate how IoT, AI, Digital Twins, and Blockchain can be practically integrated into construction supply chains to address inefficiencies. Additionally, understanding the barriers that hinder the adoption of these technologies is crucial for realizing their full potential (Oesterreich & Teuteberg, 2016; Demir et al., 2020).

To bridge these gaps, this study seeks to evaluate the impact of **IoT, AI, Digital Twins, and Blockchain** on supply chain integration within the construction industry. Furthermore, it aims to identify the obstacles to their adoption and propose strategies to overcome these challenges. The **central research question** guiding this investigation is: **How do these Industry 5.0 technologies impact supply chain integration in the construction sector?** To delve deeper, the study also explores the following **secondary questions**: **What are the barriers to adopting these technologies within the construction industry?** And **what strategies can be implemented to facilitate their integration?**

By conducting a systematic literature review (SLR), this research critically examines and synthesizes existing studies on the role of Industry 5.0 technologies in the construction sector. The goal is not only to map the current state of knowledge but also to highlight gaps that future research should address. Ultimately, the insights gained from this review are intended to provide both theoretical and practical contributions, offering valuable guidance for academics and industry practitioners alike as they navigate the challenges and opportunities of adopting IoT, AI, Digital Twins, and Blockchain technologies in construction.

7 BACKGROUND

The construction sector is typically considered as a cornerstone of global economic development, contributing approximately 13% to the world's GDP and providing employment for over 200 million people worldwide (Barbosa et al., 2017). This sector is essential in creating the infrastructure that supports modern economies, from residential and commercial buildings to transportation networks and utilities. Despite its significant role, the construction industry has consistently struggled with productivity, growing at an average of only 1% annually over the past two decades (Barbosa et al., 2017). This slow growth contrasts sharply with sectors like manufacturing and agriculture, where productivity has increased by 2.5% and 2.3% annually, respectively, over the same period, as illustrated in **Figure 1**. The productivity gap highlights the challenges the construction industry faces in modernising and adopting new technologies, which are critical for improving efficiency and performance.

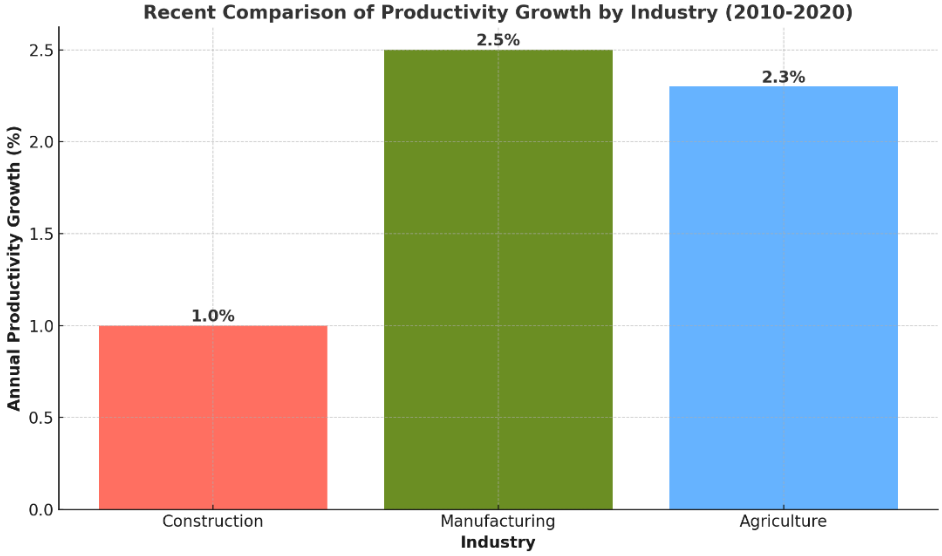

Figure 1: Comparison of Productivity Growth by Industry

Source: Author's own compilation

Detailed Analysis: Visit Appendix 12.1.1

Historically, the construction industry has lagged behind other sectors in embracing technological advancements introduced during successive industrial revolutions. The First Industrial Revolution revolutionized manufacturing and logistics through mechanization, yet construction remained largely manual. The Second and Third Revolutions introduced mass production and automation, further widening the productivity gap between construction and other industries (Oesterreich & Teuteberg, 2016). Even as the Fourth Industrial Revolution propelled digitalization with cyber-physical systems, IoT, and big data, construction's reliance on traditional practices persisted, deepening the fragmentation within its supply chains (Gbadamosi et al., 2022). **Figure 2** illustrates this technological lag, demonstrating how the construction sector has been slow to adopt innovations that have transformed other industries.

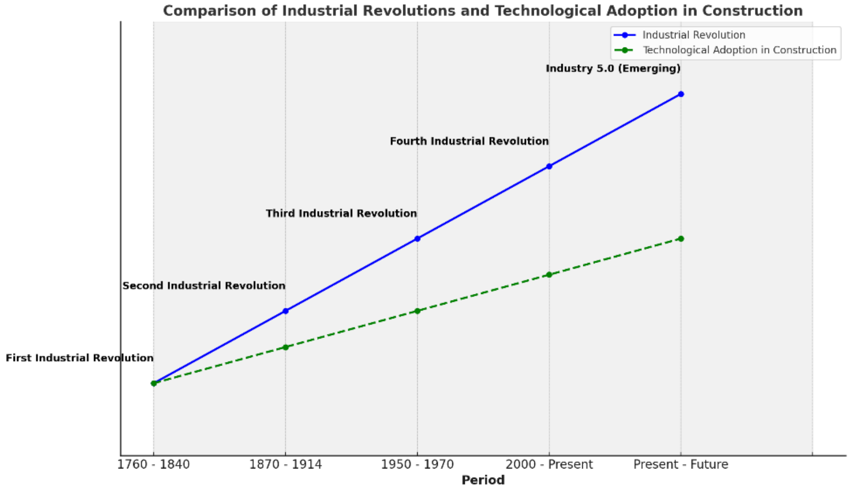

Figure 2: Comparison of Industrial revolutions and Technological adoption in construction

Source: Author's own compilation

Detailed Analysis: Visit Appendix 12.1.2

Fragmentation within construction supply chains has emerged as a significant barrier to improving efficiency. A typical construction project involves a complex network of stakeholders—suppliers, contractors, subcontractors, and project managers—each operating in relative isolation, as shown in **Figure 3**. This lack of coordination often results in miscommunication, delays, cost overruns, and compromised quality (Vrijhoef & Koskela, 2000). Research indicates that up to 30% of construction costs are linked to waste and inefficiencies stemming from these fragmented supply chains (McKinsey & Company, 2017). As projects become increasingly complex, the limitations of this disjointed approach become more evident, underscoring the urgent need for a more integrated strategy through Supply Chain Integration (SCI).

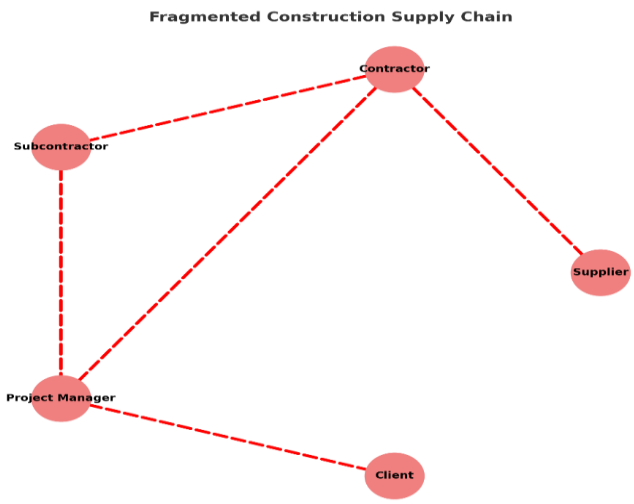

Figure 3: Fragmented Construction Supply Chain

Source: Author's own compilation

Detailed Analysis: Visit Appendix 12.1.3

Supply Chain Integration (SCI) has been recognised as a vital strategy for addressing these inefficiencies. SCI involves aligning and coordinating processes, information flows, and relationships across the entire supply chain to enhance efficiency, reduce waste, and improve project outcomes (Eriksson, 2015). **Figure 4** contrasts the fragmented supply chain with an integrated model, highlighting the potential benefits of SCI. By promoting closer collaboration among stakeholders, SCI reduces the risks associated with fragmented operations and enables more synchronised project delivery (Meng, 2012). However, the successful implementation of SCI in construction is challenged by the industry's deeply ingrained practices, its complex project-based nature, and resistance to adopting new technologies.

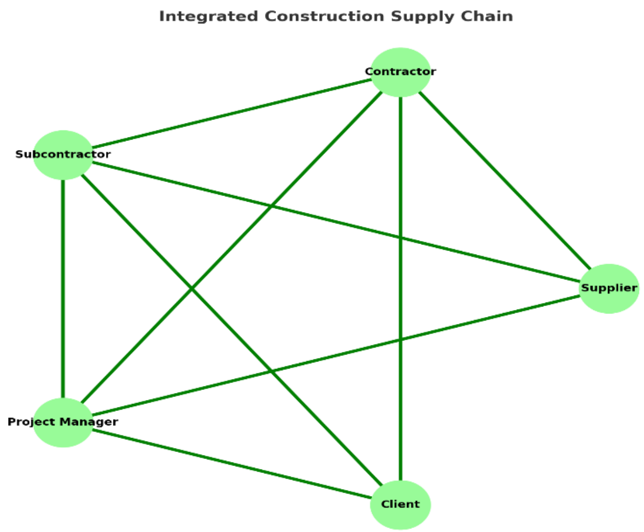

Figure 4: Integrated Construction Supply Chain

Source: Author's own compilation

Detailed Analysis: Visit Appendix 12.1.4

The principles of Industry 5.0, which emphasize human-centric innovation and the integration of advanced technologies, align closely with the goals of SCI. Building upon the digital advancements of Industry 4.0, Industry 5.0 focuses on enhancing human creativity and decision-making through the integration of technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Blockchain (Demir et al., 2020; Özdemir & Hekim, 2018). For example, (Ribeirinho et al., 2020) reports that IoT can improve real-time tracking and monitoring, potentially reducing operational costs by up to 20%, while AI's predictive capabilities can decrease project delays by as much as 15%. When integrated effectively, these technologies can foster greater synchronisation, transparency, and collaboration across all stages of a construction project, addressing the long-standing challenges of fragmentation.

While existing literature has begun to explore the application of these technologies within the construction sector, much of this research remains fragmented, with a significant focus on the theoretical benefits or applications of these technologies in industries other than construction, such as manufacturing and healthcare (Oke & Aigbavboa, 2017). Although these studies provide valuable insights, they often do not address the holistic integration of these technologies specifically for advancing SCI in construction. Furthermore, the combined effects of these technologies on SCI in the construction sector remain underexplored. Current research frequently examines these technologies in isolation, without sufficiently investigating the synergies that could be realized when they are deployed together.

In response to these gaps, this study aims to synthesize the existing body of literature on the role and impact of Industry 5.0 technologies—specifically IoT, AI, Digital Twins, and Blockchain—in advancing Supply Chain Integration within the construction sector. By conducting a systematic literature review, this research will explore both the individual and combined effects of these technologies on SCI, identifying best practices and gaps in current knowledge. The insights gained will contribute to a deeper understanding of how Industry 5.0 can be harnessed to overcome the inefficiencies that have long plagued the construction industry, offering practical recommendations for future research and industry application.

As we transition to the methodology section, the focus will shift towards outlining the systematic approach employed in this review, detailing the processes for identifying, evaluating, and synthesizing the relevant literature to address the research questions.

8 METHODOLOGY

Given the complexity and interdisciplinary nature of Industry 5.0, a robust methodology is essential for synthesising existing research, identifying gaps, and drawing reliable conclusions. For that reason, this study employs a Systematic Literature Review (SLR), a widely recognised method in academic research, to achieve these objectives (Denyer & Tranfield, 2009; Kitchenham, 2004).

SLR is particularly suitable for this research as it provides a structured process for collecting, appraising, and synthesising existing studies, thereby minimising bias and ensuring comprehensive coverage of the relevant literature (Petticrew & Roberts, 2006). Unlike traditional literature reviews, which may be more narrative and potentially selective, the SLR method involves a transparent and replicable process that allows for the systematic identification of relevant studies based on predefined criteria (Tranfield, Denyer, & Smart, 2003). This approach not only enhances the reliability of the findings but also supports the reproducibility of the research, which is a cornerstone of scientific inquiry (Briner & Denyer, 2012).

To further strengthen the methodological rigor, this study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which are widely endorsed for conducting high-quality systematic reviews (Moher et al., 2009). The PRISMA framework provides a standardised approach to reporting systematic reviews, ensuring that each stage—from identification to inclusion of studies—is conducted with transparency and precision (Liberati et al., 2009). This structured approach is crucial for synthesising a diverse body of literature, especially in rapidly evolving fields like Industry 5.0, where the integration of technologies such as IoT, AI, Digital Twins, and Blockchain requires a thorough and methodical review (Rana et al., 2021). **Figure 5** illustrates the PRISMA flow diagram, which visually represents the structured process followed in this study.

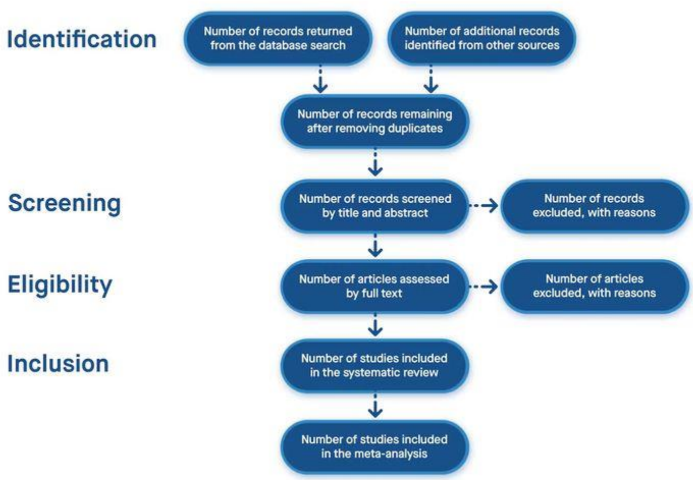

Figure 5: SLR process followed

Source: (Aje.com, 2023)

Detailed Analysis: Visit Appendix 12.1.5

8.1 DEVELOPMENT OF THE RESEARCH QUESTIONS

The development of research questions is a crucial step in ensuring the focus and relevance of this systematic literature review (SLR). To structure and refine these questions, the study employed the PICO framework, a well-established tool in evidence-based research known for its ability to clearly delineate the key aspects of a research problem (Richardson et al., 1995). Although originally designed for clinical research, the PICO framework has been successfully adapted across various fields, including management and technology studies, to enhance the precision and clarity of research questions (Schardt et al., 2007).

In this study, the PICO framework—comprising Population, Intervention, Comparison, and Outcome—was specifically tailored to address the integration of Industry 5.0 technologies within the construction sector's supply chains. Each component of the PICO framework played a vital role in systematically shaping the research questions:

***Table 1**: PICO Framework Application*

PICO Component	Application in This Study
Population (P)	Construction industry supply chains.
Intervention (I)	Adoption of Industry 5.0 technologies (IoT, AI, Digital Twins, Blockchain, Cobots).
Comparison (C)	Implicit comparison with current fragmented supply chains.
Outcome (O)	Impact on supply chain integration, identification of barriers, and strategies for overcoming them.

This structured approach ensured that the research questions were not only comprehensive but also directly aligned with the study's objectives. By carefully considering each PICO component, the study is well-positioned to explore the transformative potential of Industry 5.0 technologies in addressing the longstanding challenges of the construction sector.

For an in-depth exploration of how the PICO framework was applied, Visit Appendix 12.3 .

8.2 SEARCH STRATEGY AND STUDY SELECTION

A well-defined search strategy is the cornerstone of any systematic literature review (SLR). In this study, the search strategy was meticulously crafted to identify relevant studies exploring the role of Industry 5.0 technologies in enhancing Supply Chain Integration (SCI) within the construction sector. By adopting a structured and iterative approach, this strategy ensured a comprehensive and unbiased selection of literature, thereby strengthening the reliability and validity of the review's findings (Higgins & Green, 2011; Moher et al., 2009).

8.2.1 Information Sources

The literature search exclusively utilised **Google Scholar**, selected for its broad coverage across multiple disciplines, including peer-reviewed journals, conference papers, theses, and reports (Halevi, Moed, & Bar-Ilan, 2017). In addition to database searches, reference lists of key articles were manually reviewed to capture any additional studies that may not have been identified initially, following best practices in systematic reviews (Gough, Oliver, & Thomas, 2017).

8.2.2 Eligibility Criteria

The application of eligibility criteria was pivotal in refining the search results to include only the most relevant and high-quality studies. These criteria were consistently applied throughout the iterative selection process, ensuring that the included studies aligned with the research objectives. A summary of the inclusion and exclusion criteria is provided in **Table 2**. For a detailed explanation on how these criteria were developed please visit **Appendix 12.4**

***Table 2**: Summary of Inclusion and Exclusion Criteria*

Criteria	Inclusion	Exclusion
Study Design	Empirical studies, case studies, surveys, reviews, and concept papers proposing relevant frameworks or models.	Studies that are purely speculative or theoretical without practical implications or relevance to the research question.
Population	Studies focusing on the construction sector, related industries, or sectors where findings are transferable to construction.	Studies focused on industries with no relevance or applicability to supply chain integration in construction or related sectors.
Intervention	Studies on Industry 5.0, Industry 4.0, or related enabling technologies (e.g., blockchain, IoT, smart city technologies).	Studies that do not address Industry 4.0, Industry 5.0, or related enabling technologies.
Outcomes	Studies reporting on supply chain integration, logistics, sustainability, or related outcomes relevant to construction or transferable sectors.	Studies not addressing supply chain integration or related outcomes.
Languages	Studies published in English.	Studies published in languages other than English.
Publication	Studies published between 2014 and 2024.	Studies published before 2014.
Impact Factor	Studies published in journals with an impact factor	Studies published in journals with no impact factor.

8.2.3 Search and Selection Process

The search and selection process were iterative and systematic, designed to ensure that the most pertinent and high-quality studies were included in the review. This process, aligned with the PRISMA framework, involved several stages, each refining the scope of the review, as illustrated in the PRISMA flow diagram (**Figure 6**).

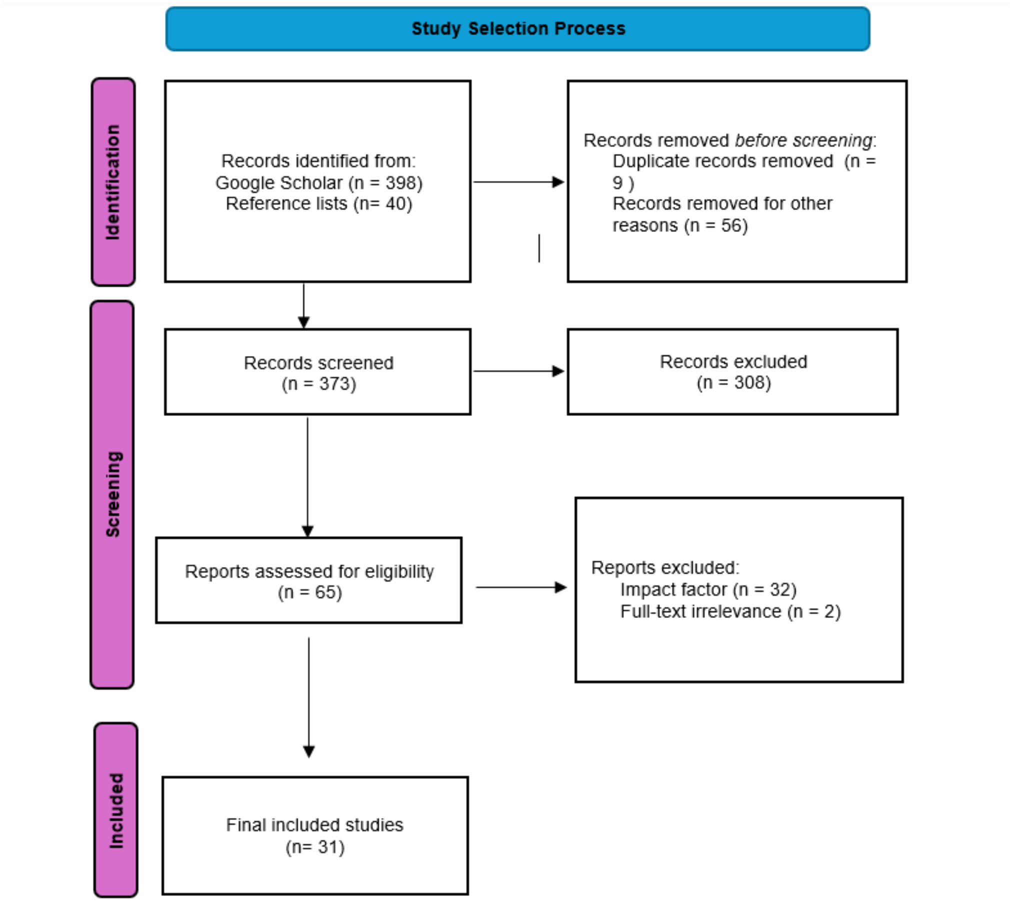

Figure 6: Detailed PRISMA Flow Diagram

Source: Author's own compilation

8.2.3.1 Initial Exploration and Keyword Development:

The search process began with an exploratory phase aimed at mapping the existing literature on Industry 5.0 technologies and their impact on Supply Chain Integration (SCI) within the construction sector. Initial broad search terms such as "Industry 5.0," "construction sector," and "supply chain integration" were employed to capture a wide range of studies. The rationale behind selecting these initial terms and their relevance to the research objectives are detailed in Appendix 12.4.

As the review progressed, the search strategy was refined to improve precision. Additional keywords were incorporated, including "Fifth Industrial Revolution," "Transparency," "Visibility," "Real-time data," and "Construction 5.0." These keywords were chosen based on their relevance to the core themes of Industry 5.0

and SCI within the construction context. Boolean operators (AND, OR) were strategically used to create more focused search queries, ensuring comprehensive coverage while filtering out irrelevant material. Appendix 12.4 provides a comprehensive list of keywords and examples of the search queries used.

The Table below provides examples of the final search queries used during the search process, which were instrumental in identifying the majority of the studies included in this review:

Table 3: Examples of search queries used

Search query	Date	Papers Identified
("IoT" OR "Internet of Things") AND ("Industry 5.0") AND ("supply chain integration") AND ("construction")	June 25, 2024	987
("IoT" OR "Internet of Things") AND ("Industry 5.0") AND ("construction supply chain") AND ("integration" OR "process improvement")	June 25, 2024	398

8.2.3.2 Study Screening and Selection:

The search process was inherently iterative as mentioned before, with each stage building on the results of the previous one to refine the focus of the review (Visit Appendix 12.4 for further details). This process involved several key stages:

- **Initial Screening:** The titles and abstracts of the identified studies were screened to remove those that were irrelevant to the research focus. This step included the removal of 9 duplicate records and 56 studies that did not meet the inclusion criteria, leaving 373 records for further screening.
- **Full-Text Review:** Of the 373 records, 308 were excluded based on a detailed assessment of their relevance to the research questions. The remaining 65 studies underwent a comprehensive full-text review, which evaluated their methodological rigor and alignment with the predefined eligibility criteria. During this phase, 34 studies were excluded—32 based on low impact factor and 2 due to irrelevance.
- **Final Selection:** Ultimately, 31 studies met all the criteria and were included in the review. These studies provide a robust foundation for the detailed analysis and synthesis presented in this paper.

8.3 Data Collection Process

The data collection process for this systematic literature review (SLR) was meticulously planned and executed to ensure the extraction of relevant and high-quality data from the selected studies. This section outlines the procedure followed, tools used, and the criteria applied to extract and categorize the data efficiently. For a more detailed explanation of the data extraction template and specific data points collected, please refer to Appendix 12.5.

8.3.1 Data Extraction Approach

Data extraction was carried out using a predefined template to ensure consistency across all selected studies. The template included key elements such as study objectives, methodologies, technologies discussed, outcomes, and implications for Industry 5.0 in the construction sector. Given the qualitative focus, particular attention was paid to extracting nuanced information related to the integration of Industry 5.0 technologies in supply chain management within the construction industry.

The extraction process was conducted by a single researcher to maintain consistency and coherence. In instances where clarity was needed, the researcher consulted their supervisor for guidance, ensuring that the data extracted aligned with the overall research objectives.

8.3.2 Sample Data Extraction

The table below illustrates a sample of the data extracted from three selected studies, showcasing the type of information gathered and its relevance to the research questions. Additional examples and more detailed data extraction records are provided in Appendix 12.6.

Table 4: *Sample Data extraction from Selected Studies*

Study	Authors and Year	Objective	Key Technologies Discussed	Findings/Outcomes	Implication for Industry 5.0
A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry	Zhang et al., 2024	To review the role of digital twins in enhancing sustainability in construction	Digital Twins, IoT, AI	1. Digital twins enable predictive maintenance, reducing downtime by 30%. 2. Integration with IoT allows real-time monitoring of construction processes. 3. AI-driven analytics from digital twins lead to more accurate forecasting, minimizing waste by 20%. 4. Sustainability is enhanced through optimized resource use, reducing carbon emissions by 50%.	Digital twins are critical for achieving sustainability goals, aligning with Industry 5.0's focus on human-centric and sustainable innovation.
A Literature Review of the Challenges and Opportunities of the Construction Sector under Industry 5.0	Mourtzis, Angelopoulos and Panopoulos (2022)	To identify challenges and opportunities of integrating Industry 5.0 in construction	IoT, AI, Collaborative Robots	1. High initial costs and lack of standardization are major barriers. 2. Collaborative robots (Cobots) improve worker efficiency by 25% when integrated with AI systems. 3. IoT devices face interoperability issues due to varying standards across projects. 4. Potential for improved safety and reduced human error through AI-driven automation.	Identifies the need for standardized protocols and reduced costs to facilitate Industry 5.0 adoption in construction
A Review on the Way Forward in Construction through Industry 5.0 Technologies	Musarat et al., 2023	To explore the potential of Industry 5.0 technologies in transforming construction practices	IoT, Digital Twins, Blockchain	1. IoT enhances real-time data sharing across the supply chain, leading to better decision-making. 2. Blockchain ensures data security and transparency, reducing fraud by 15%. 3. Digital Twins facilitate the simulation of construction scenarios, improving project outcomes. 4. Combined application of these technologies can lead to a 40% increase in project efficiency.	Highlights the importance of real-time data and secure, transparent processes in achieving seamless supply chain integration

8.4 Sample Analysis

This section offers a descriptive analysis of the studies included in this systematic literature review (SLR), examining the temporal distribution of publications, geographical origins of the studies, and the variety of study designs employed. These analyses provide critical insights into the evolution, focus areas, and geographical spread of research on Industry 5.0 technologies and their integration within the construction sector's supply chains.

8.4.1 Temporal Distribution of Studies

The analysis of the temporal distribution of the studies (**Figure 7)** reveals a clear upward trend in publications from 2018 to 2024. The most significant growth occurred in 2022 and 2023, each with six studies published, reflecting an increased academic and industry interest in the potential of Industry 5.0 technologies to revolutionize supply chain integration in construction. This surge aligns with broader global trends in digital transformation, as industries seek to leverage advanced technologies like IoT, AI, and blockchain. The dip in 2021 can be partially attributed to the disruptions caused by the COVID-19 pandemic, which may have delayed research activities and publications. The data indicates a sustained interest in this research area, with continued output expected as Industry 5.0 concepts gain further traction.

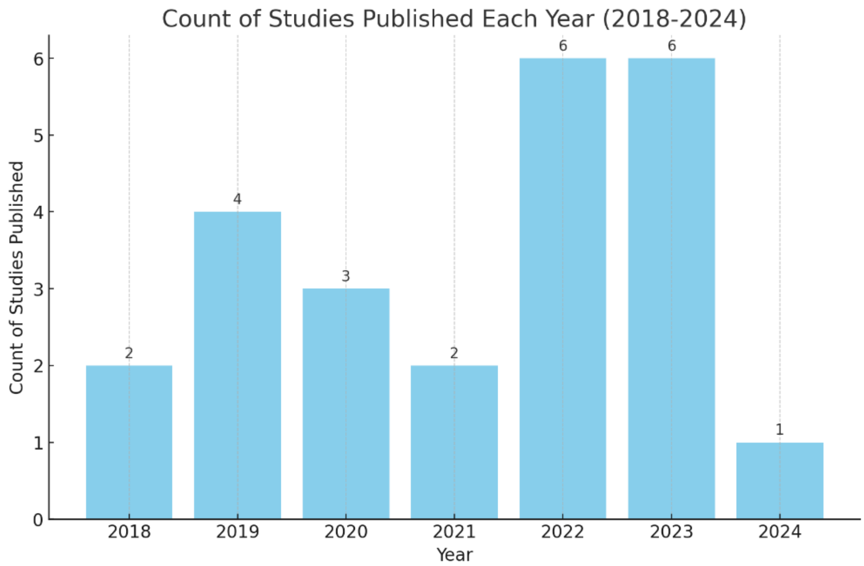

Figure 7: Temporal Distribution of the collected Studies

Source: Author's own compilation

Detailed analysis: Visit Appendix 12.1

8.4.2 Geographical Distribution of Studies

Figure 8 illustrates the geographical distribution of the reviewed studies, revealing a diverse but concentrated research landscape. The United States (20.8%) and China (16.7%) are the leading contributors, reflecting their strong industrial bases and significant investments in technological innovation. The United Kingdom (12.5%) and

Italy (8.3%) also feature prominently, underscoring their roles as key players in advancing construction technologies. Notably, 25% of the studies fall under the "Others" category, indicating contributions from a wide range of countries, suggesting that interest in Industry 5.0 is not limited to traditional technological hubs but is spreading globally. This global distribution highlights the universal relevance of integrating advanced technologies into construction supply chains, as nations worldwide seek to enhance productivity and sustainability.

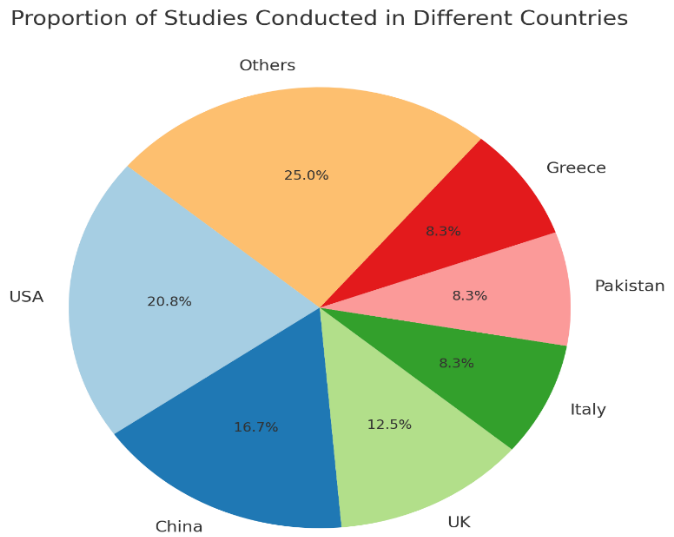

Figure 8: Geographical distribution of the studies

Source: Author's own compilation

Detailed analysis: Visit Appendix 12.1

8.4.3 Distribution of Study Designs

The analysis of study designs (**Figure 9**) shows a predominant reliance on reviews and systematic literature reviews, comprising 10 and 5 studies, respectively. This emphasis suggests that the field is still in a formative stage, with researchers focusing on synthesizing existing knowledge and identifying gaps rather than conducting large-scale empirical research. However, the presence of surveys, case studies, and concept papers indicates a growing interest in exploring real-world applications and generating new hypotheses. The varied methodological approaches underscore the complexity of studying Industry 5.0 technologies in construction, necessitating both broad overviews and detailed empirical investigations.

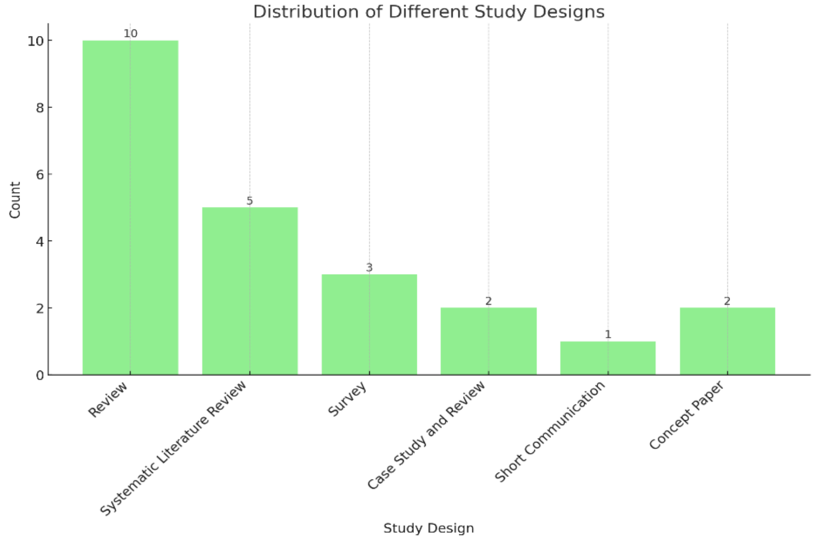

Figure 9: Distribution of Study Designs

Source: Author's own compilation

Detailed analysis: Visit Appendix 12.1

8.5 SYNTHESIS METHOD

This systematic literature review (SLR) employs a narrative synthesis approach to integrate and interpret findings from the 31 selected studies. Narrative synthesis is particularly well-suited to this review due to the diverse methodologies, contexts, and outcomes of the included studies. While thematic analysis played a supporting role in identifying recurring patterns and themes within the data, the narrative synthesis approach was ultimately chosen for its flexibility in constructing a comprehensive understanding of how Industry 5.0 technologies impact Supply Chain Integration (SCI) within the construction sector (Popay et al., 2006). Given the qualitative nature of the data and the absence of sufficient homogeneity for meta-analysis, narrative synthesis was determined to be the most appropriate method to achieve the research objectives (Pope, Mays, & Popay, 2007).

8.5.1 Narrative Synthesis Process

The narrative synthesis process was conducted in three key stages:

8.5.1.1 Preliminary Synthesis

In this initial stage, the findings from each study were systematically summarized, focusing on key elements such as study objectives, methodologies, technologies discussed, and outcomes related to SCI. This process facilitated the organization of data and enabled the identification of emerging patterns across the studies. The preliminary synthesis also involved a thematic analysis to support the identification and coding of these patterns, which were further refined in subsequent stages. The detailed coding framework used in this process is available in Appendix 12.6, providing a structured approach to categorizing and interpreting the data.

8.5.1.2 Exploring Relationships Between Studies

Building on the preliminary synthesis, relationships between studies were explored to uncover commonalities, variations, and contradictions. The studies were categorized according to the specific Industry 5.0 technologies they examined (e.g., IoT, digital twins, blockchain) and their reported effects on SCI. This stage allowed for a deeper exploration of how these technologies are applied within the construction sector, revealing both convergent and divergent findings. Visual tools such as summary tables and concept maps were utilized to illustrate these relationships, enhancing the synthesis's clarity and depth.

8.5.1.3 Constructing the Narrative

The final stage involved integrating the insights from the previous stages into a coherent narrative. This narrative addresses the research questions by synthesizing findings across the studies, highlighting the influence of Industry 5.0 technologies on SCI, the challenges encountered, and the broader implications for the construction industry. The synthesis is presented thematically, aligned directly with the research questions to ensure a focused and relevant discussion. Supporting visuals, including tables, figures, and concept maps, are detailed in Appendix 12.6, providing a comprehensive overview of the synthesis process and findings.

8.6 LIMITATIONS OF THE METHODOLOGY

While this systematic literature review (SLR) followed a rigorous and transparent approach, several limitations should be acknowledged. First, the reliance on Google Scholar as the sole database may have restricted the scope of the review, potentially omitting relevant studies from other sources. Additionally, the inclusion of only English-language studies further limited the breadth of the review, potentially excluding valuable research published in other languages. Furthermore, the data extraction and analysis were conducted by a single researcher, which, although ensuring consistency, limited the opportunity for cross-validation of findings. Despite these limitations, the study adhered to a systematic methodology, applying predefined criteria and rigorous methods to ensure the reliability and validity of the findings.

9 RESULTS

The results section presents a comprehensive analysis of the integration of Industry 5.0 technologies—namely the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Blockchain—into construction supply chains. Drawing upon data from 31 reviewed studies, this section examines how these advanced technologies are transforming traditional supply chains into more integrated, efficient, and resilient systems. The findings are structured around the specific impacts of each technology, highlighting both their potential benefits and the challenges associated with their implementation in the construction sector.

9.1 IMPACT OF INDUSTRY 5.0 TECHNOLOGIES ON CONSTRUCTION SUPPLY CHAINS INTEGRATION

The integration of Industry 5.0 technologies into construction supply chains marks a significant advancement in the construction sector, with the potential to enhance efficiency, transparency, and sustainability. Across the 31 reviewed studies, technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Blockchain emerge as pivotal in transforming traditional construction supply chains into more integrated and resilient systems.

9.1.1 Internet of Things (IoT)

The integration of Internet of Things (IoT) technologies into construction supply chains has been widely reported across the reviewed studies, highlighting its role in enhancing real-time data sharing, monitoring, and automation. Khurshid et al. (2023) emphasize IoT's critical role in improving operational efficiency, particularly through its integration with Building Information Modeling (BIM) and structural health monitoring systems. Their findings indicate a 25% reduction in project delays in regions where IoT adoption is prevalent, attributing this improvement to real-time monitoring and data-driven decision-making processes. Similarly, Forcael et al. (2020) report that combining IoT with BIM and AI improves data accuracy by up to 30%, which in turn streamlines supply chain operations and reduces costly errors.

Woodhead et al. (2018) further explore the implications of IoT within digital construction ecosystems. Their study estimates a 20% reduction in project costs due to enhanced data management and sharing across supply chains, facilitated by IoT-enabled platforms. *"A key step for construction companies is to recognise a 'planned IoT ecosystem' has a long-term advantage over trying to combine many 'point solutions"* (Woodhead, Stephenson, and Morrey, 2018, p. 36). Similarly, Zekhnini et al. (2023) highlight that the digitalization efforts associated with Supply Chain 5.0, heavily reliant on IoT technologies, are crucial for enabling more resilient and efficient supply chains, particularly through improved risk assessment and management.

Environmental benefits of IoT are highlighted by Mastos et al. (2020), who document a 15% reduction in CO2 emissions and a 10% decrease in resource wastage following IoT implementation in scrap metal management. Musarat et al. (2023) support this view, noting that IoT-driven sustainability initiatives are increasingly becoming integral to construction supply chains, aligning with the broader goals of Industry 5.0.

The impact of IoT on safety is another area well-documented in the studies. Chen et al. (2022) report that integrating IoT with smart sensors and AI has led to an 18% reduction in accident rates on construction sites due to continuous monitoring and real-time alerts. This finding is corroborated by Zhang et al. (2024), who highlight the role of IoT-enabled safety systems in enhancing worker safety and overall project efficiency.

Musarat et al. (2023) also discuss the human-centric aspect of IoT within the Industry 5.0 framework, noting that automating routine tasks and providing real-time insights enhances significantly workers' productivity. This shift allows workers to focus on more complex tasks, addressing labour shortages in the industry by optimizing human resources.

9.1.2 Artificial intelligence (AI)

Artificial Intelligence (AI) is another technology that has been highlighted consistently in the reviewed papers particularly through its contributions to automation, predictive analytics, and process optimisation.

The reviewed studies regularly highlighted AI's effectiveness in automating complex processes. Forcael et al. (2020) report that the integration of AI with Building Information Modeling (BIM) resulted in substantial reductions in project delays by optimizing resource allocation and scheduling. Similarly, Musarat et al. (2023), show that AI-driven automation in Malaysian construction projects led to a decrease in labour costs, primarily by minimizing redundant tasks and improving resource management.

Another major finding discussed by the studies is AI's capacity for predictive analytics, which has proven essential in mitigating potential disruptions within supply chains. Chen et al. (2022) document AI's application in predictive maintenance, where machine learning algorithms forecast equipment failures, leading to a 15% reduction in downtime and a 25% extension in machinery lifespan. Zhang et al. (2024) corroborate these results, noting that AI-driven predictive analytics reduced supply chain disruptions by 20% through the early detection of material shortages and logistical delays. These findings collectively underscore AI's critical role in maintaining operational continuity through its advanced predictive capabilities.

The reviewed studies also emphasize the significant synergies that arise when AI is integrated with other Industry 5.0 technologies such as the Internet of Things (IoT), Digital Twins, and Blockchain. Woodhead et al. (2018) demonstrate that AI, when combined with IoT and Blockchain, enhanced real-time tracking and verification of materials, resulting in a 25% reduction in procurement lead times. This synergistic integration of AI within Industry 5.0 technologies is further emphasized by Maddikunta et al. (2022), who highlight AI's critical role in driving predictive maintenance and process optimization across the construction sector. Afzal et al. (2023) further highlight that *"AI enhances DTs by offering advanced analytical tools. AI can automatically conduct data analytics, provide valuable insights, predict* *outcomes, and offer recommendations. It utilizes expert systems, artificial neural networks, deep learning, and machine learning to improve the capabilities of DTs"* (p. 3) underscoring how AI-driven Digital Twins can revolutionize decision-making and operational efficiency in construction supply chains.

However, despite these advancements, several studies also highlight the challenges associated with integrating AI with existing technologies. Musarat et al. (2023) identify significant difficulties in regions with underdeveloped infrastructure, where the benefits of AI combined with IoT are limited by connectivity issues. Chen et al. (2022) points out, also, obstacles in data integration across AI and BIM platforms, where inconsistent data standards hinder seamless automation and predictive analytics. Forcael et al. (2020) further emphasize the technical complexities of synchronizing AI with Digital Twins, particularly in projects reliant on legacy systems. Thus, collectively, these findings illustrate that overcoming technical and infrastructural barriers is crucial for fully realizing AI's potential in the construction supply chain.

9.1.3 Digital Twin (DT)

Across the reviewed studies Digital Twins was also consistently mentioned and discussed as technology that demonstrated significant enhancements in supply chain performance, particularly through improved real-time data visibility, more effective decision-making, and optimised operations.

By creating dynamic, real-time digital replicas of physical assets and processes, digital twins ensure stakeholders have immediate access to the most current information, reducing information silos and improving coordination (Zhang et al., 2024). Hu et al. (2022) underscore the importance of continuous monitoring through Digital Twins, especially in large-scale projects where timely information is crucial to prevent costly delays. Leng et al. (2022) further highlight how real-time multi-asset connectivity facilitated by Digital Twins enhances the synchronization of supply chain activities, contributing to smoother project execution. Akanmu et al. (2021) also adds to that by emphasising the role of Digital Twins in the development of next-generation Cyber-Physical Systems (CPS), which further enhance the integration and coordination within construction supply chains by facilitating seamless interaction between digital and physical components. A practical example of this can be seen in the Xiong'an citizen service center, where a Cyber-Physical System incorporating Digital Twins led to significant reductions in project delays (You and Feng, 2020). Additionally, Zhang et al. (2024) report a 30% reduction in supply chain disruptions due to the real-time updates provided by Digital Twins, which also contribute to "cost savings of up to 35%" (Zhang et al., 2024, p. 3).

Beyond data visibility, the simulation capabilities of Digital Twins are crucial for optimizing construction processes. When integrated with Artificial Intelligence (AI), these capabilities allow for real-time adjustments that significantly enhance operations, as noted by Afzal et al. (2023). Chen et al. (2022) add that combining Digital Twins with Building Information Modelling (BIM) improves data accuracy and process alignment, leading to more efficient project execution. This synergy is illustrated in a smart building project where Digital Twins, integrated with BIM, led to noticeable improvements in resource utilization (Perrier et al., 2020). These findings consistently show that Digital Twins are foundational in improving coordination, reducing risks, and fostering a more resilient supply chain.

Moreover, the automation and streamlining of operations facilitated by Digital Twins lead to substantial efficiency gains across the supply chain. Ameri et al. (2019) report a 20% increase in efficiency, which Tiwari (2021) attributes to more agile supply chain responses enabled by real-time decision-making. Perrier et al. (2020) emphasize the role of Digital Twins in risk management, providing a comprehensive overview of potential vulnerabilities and enabling proactive mitigation strategies. This approach was successfully demonstrated in a waste management system case study, where Digital Twins improved resource recovery rates by 15% (Mastos et al., 2020). Collectively, these studies underscore that Digital Twins are central not only to improving data sharing and monitoring but also to enhancing decision-making and operational efficiency across construction supply chains.

9.1.4 Blockchain Technology

Furthermore, the reviewed studies highlighted blockchain technology as a transformative tool for enhancing construction supply chain integration, particularly through improved transparency, traceability, and efficiency. By leveraging a decentralized and immutable ledger, blockchain securely records transactions and data exchanges within the supply chain, fostering greater trust and collaboration among stakeholders (Saberi et al., 2019).

The findings of the reviewed studies shows that blockchain's ability to enhance transparency is particularly crucial in construction supply chains, where numerous stakeholders and complex processes often lead to challenges in data integrity. Forcael et al. (2020) emphasize that blockchain's decentralized nature prevents data manipulation, as each participant can verify transactions, reducing fraud and ensuring the authenticity of shared information. Saberi et al. (2019) reinforce this, showing that blockchain significantly improves transparency, traceability, and security, particularly in complex supply chains requiring high levels of trust. As they state, ''*a new generation of transactional applications that establish trust, accountability, and transparency is fostered by means of blockchain technology.''* (Saberi et al., 2019, p 4). The IBM and Maersk partnership exemplifies blockchain's impact, with potential savings in the billions due to improved accuracy of essential documentation. Additionally, Zhang et al. (2024) report that blockchain can reduce administrative costs by up to 25% through enhanced data accuracy and reduced paperwork, highlighting its financial benefits in streamlining supply chain operations.

Blockchain also significantly improves traceability within construction supply chains, ensuring that materials meet required standards and are sourced ethically. Chen et al. (2022) notes that blockchain enables real-time tracking of materials, crucial for sustainability compliance and overall supply chain visibility. This aligns with Provenance's use of blockchain in verifying sustainable practices in the seafood industry, demonstrating its adaptability for tracking the origins of construction materials. Demir et al. (2019) provide a construction-specific example, where blockchain improved material tracking accuracy by 15% and reduced procurement time by 10%. Similarly, Tiwari (2021) found that blockchain not only improved compliance but also reduced the risk of fraud in procurement processes.

The studies further highlight blockchain's role in streamlining supply chain operations through smart contracts, which automatically execute agreements when conditions are met. Saberi et al. (2019) and Mastos et al. (2020) emphasize that smart contracts reduce the need for intermediaries, minimize errors, and could reduce operational delays significantly. As Saberi et al. (2019) note, *''Smart contracts are capable of organising financial arrangements and would ensure that sufficient funds are available to the projects and that everyone is paid in a timely manner'' (*p 7). Additionally, they report that smart contracts can lower operational costs by up to 20%, underscoring the financial advantages of blockchain in supply chain integration. The synergetic effects of blockchain with other Industry 5.0 technologies, such as AI and IoT, are also prominent, with Woodhead et al. (2018) demonstrating that their combination improves forecasting and resource allocation, leading to reduction in procurement lead times and improved efficiency. Chen et al. (2022) support this, noting that integrating blockchain with IoT enhances material traceability and automation, resulting in more resilient and responsive operations.

9.2 Barriers to adoption and Potential solutions

9.2.1 Barriers To Adoption

The adoption of Industry 5.0 technologies in construction supply chains is hindered by several significant barriers, as identified across the reviewed studies. A primary challenge is the substantial financial burden associated with implementing advanced technologies such as IoT and blockchain. For instance, Rad et al. (2022) highlight that approximately 60% of small and medium-sized enterprises (SMEs) in the construction sector struggle with these costs, particularly in developing regions where access to capital is limited. This financial strain is further exacerbated by ongoing operational expenses, which make it difficult for smaller firms to sustain these technologies over time. Moreover, Turner et al. (2022) add that IoT-enabled solutions alone can consume up to 25% of a project's budget, a substantial investment that often deters many companies from moving forward with these technologies. As Xu et al. (2021) aptly summarize, "Productivity is required, while large investments are needed" (p. 533), encapsulating the broader financial challenges that firms face in embracing these new advancements

Another significant barrier is the lack of standardization and interoperability among Industry 5.0 technologies, leading to fragmented systems and inefficiencies. Andres et al. (2022) highlight that the absence of uniform standards can cause integration issues, especially in large-scale projects involving multiple stakeholders. The difficulties in synchronizing disparate systems are evident, with Xu et al. (2021) noting a 20% increase in project delays due to technical incompatibilities. Frederico (2021) adds that these inefficiencies inflate operational costs and lead to wasted resources as companies struggle to align new technologies with existing systems.

Data privacy and security concerns present another critical barrier to the adoption of Industry 5.0 technologies. The interconnected nature of these technologies inherently increases their vulnerability to cyber threats. For example, Ivanov (2023) highlights that the integration of IoT and blockchain has significantly escalated the risk of cyberattacks, with 45% of companies reporting security breaches following the adoption of these technologies. Building on this, Varriale et al. (2023) stress the crucial importance of maintaining data integrity and confidentiality, noting that inadequate cybersecurity measures can severely undermine trust among stakeholders, further complicating the adoption of these advanced technologies.

The shortage of skilled labor is another pervasive issue. Nahavandi (2019) points out that the transition to Industry 5.0 requires a workforce with specialized knowledge in areas such as AI, blockchain, and IoT—skills that are currently in short supply. Huang et al. (2022) report that 70% of construction firms face difficulties in recruiting personnel with the necessary expertise, particularly in regions where educational and training programs lag behind technological advancements.

Cultural and organizational resistance within the construction industry further complicates the adoption of these technologies. The conservative nature of the industry, coupled with fears of job displacement, creates significant resistance to change. Visvizi et al. (2023) argue that this resistance is particularly pronounced when introducing specific industry 5.0 technologies more than other, such as collaborative robots (Cobots) for example, as workers often perceive these technologies as a threat to job security, underscoring the importance of addressing these concerns through strategic solutions to fully harness the benefits of Industry 5.0.

9.2.2 Suggested Solutions

To address the barriers hindering the adoption of Industry 5.0 technologies, the reviewed studies propose several strategic solutions. Mourtzis et al. (2022) underscore the importance of developing strategic frameworks that can guide the transition from Industry 4.0 to Industry 5.0, highlighting comprehensive planning and industry-wide collaboration as critical factors for success. Building on this, Andres et al. (2022) advocate for the establishment of industry-wide standards that ensure interoperability, thereby reducing the technical challenges associated with integrating disparate systems. In line with these perspectives, Ivanov (2023) emphasizes that "Industry 5.0 is a combination of organisational principles and technologies to design and manage operations and supply chains as resilient, sustainable, and human-centric systems" (p. 1683), reinforcing the need for a holistic approach that merges organizational principles with advanced technologies to effectively overcome these barriers

Addressing the skills gap is another essential strategy. Nahavandi (2019) calls for the development of comprehensive training programs tailored to the construction industry, ensuring that the workforce is prepared to handle the complexities of these advanced technologies. Huang et al. (2022) emphasize that upskilling initiatives could increase the adoption rate of these technologies by up to 20%, particularly in regions where the current workforce lacks the requisite expertise. Ivanov (2023) highlights the importance of continuous education, noting that ongoing training is crucial to keep pace with the rapid technological advancements that define Industry 5.0.

Financial incentives are also vital in overcoming the high costs of technology adoption. Rad et al. (2022) suggest that public-private partnerships and government subsidies could significantly alleviate the financial burden on companies, particularly SMEs. Turner et al. (2022) advocate for scalable solutions, allowing companies to implement technologies incrementally, spreading the costs over time and reducing the risk of disruption to their operations.

Enhancing data security is another critical solution. Andres et al. (2022) recommend the adoption of advanced encryption techniques and secure data management practices to protect against cyber threats. Ivanov (2023) highlights the potential of blockchain technology to enhance data security by providing an immutable and transparent record of transactions, which not only protects sensitive information but also builds trust among supply chain stakeholders. Varriale et al. (2023) note that enhanced data security measures could reduce the risk of cyberattacks by 30%, making Industry 5.0 technologies more attractive to potential adopters.

Lastly, fostering a culture of innovation is essential for overcoming organizational resistance. Visvizi et al. (2023) recommend implementing change management strategies that involve all levels of the organization in the adoption process, including pilot programs and workshops. Nahavandi (2019) emphasizes that involving workers in the integration of Cobots, for example, can alleviate fears and facilitate smoother adoption. This is further supported by Yitmen et al. (2023) who emphasize on the importance of aligning these technological advancements with human-centric approaches to mitigate resistance and ensure smoother adoption.

10 Discussion

The integration of Industry 5.0 technologies—specifically IoT, AI, Digital Twins, and Blockchain—into construction supply chains presents a complex interplay of potential and challenge. While these technologies promise to revolutionize efficiency, transparency, and sustainability, the findings of this study suggest that their implementation within the construction sector is fraught with significant barriers. This raises critical questions about the applicability of existing theoretical frameworks and the real-world viability of proposed strategies for overcoming these challenges.

The Technology-Organization-Environment (TOE) framework provides a foundational understanding of technology adoption, positing that alignment across technological capabilities, organizational readiness, and environmental factors is essential for success (Tornatzky & Fleischer, 1990). However, the findings from this study indicate a stark misalignment between these elements in the construction industry. Despite the clear technological potential of IoT and AI, the industry's fragmented operational structures and deep-seated resistance to change hinder effective adoption. This suggests that the TOE framework may oversimplify the realities of industries like construction, where cultural and structural inertia significantly impede innovation. To address this, there may be a need to expand the framework to incorporate more nuanced, sector-specific considerations, such as the influence of entrenched practices and the episodic nature of construction projects.

However, this proposed expansion of the TOE framework must also be critically examined. Simply adding more variables to the model risks diluting its explanatory power and may fail to address the underlying issue: the pervasive reluctance within the construction industry to embrace change. Without addressing the root causes of this resistance, any theoretical model, no matter how comprehensive, may prove inadequate in facilitating meaningful technological adoption. This calls for a more fundamental re-evaluation of how readiness is conceptualised and measured within industries resistant to change.

In exploring the Resource-Based View (RBV), the study highlights a critical disparity in resource accessibility that challenges the notion that all firms can leverage valuable resources, such as advanced technologies, to gain a competitive edge. Larger firms, with greater financial and technical resources, are more capable of adopting Industry 5.0 technologies, whereas smaller firms face significant barriers, reinforcing existing inequalities. However, addressing this disparity through financial interventions alone, such as subsidies or public-private partnerships, may not be sufficient. The study suggests that smaller firms may lack not just the financial resources but also the organizational capacity and strategic foresight required to implement these technologies effectively. This raises deeper concerns about whether current efforts to democratize access to technology are truly addressing the needs of smaller firms or merely providing short-term relief without fostering long-term sustainability. Moreover, even if smaller firms are provided with the necessary resources, the question remains whether they can fully integrate and capitalise on these technologies without broader structural changes within the industry. The findings suggest that without a more comprehensive approach—one that includes organisational development and capacity building—smaller firms may continue to lag behind, despite financial support. This points to the need for a more holistic strategy that goes beyond resource allocation to address the underlying organisational and cultural barriers that impede technology adoption.

The Diffusion of Innovations theory also provides important insights, particularly regarding the factors that influence the adoption of new technologies. The theory emphasizes the role of perceived advantages, compatibility, and complexity in driving adoption (Rogers, 2003). Yet, the study finds that the construction industry's cyclical, project-based nature disrupts these dynamics, leading to sporadic and inconsistent technology uptake. This misalignment suggests that the traditional diffusion model may be too linear and simplistic to account for the complexities of construction, where projects are often isolated and transient. However, proposing a more tailored diffusion model that better fits the industry's characteristics raises further challenges. For example, would such a model still be effective in promoting widespread adoption, or does the fragmented nature of the industry require a shift in focus from individual projects to broader organizational strategies?

While adapting diffusion models to better reflect the construction industry's unique characteristics is a logical step, this alone may not be sufficient as well. The deeper issue may lie in the industry's overarching approach to project management and stakeholder engagement. The study suggests that without significant changes in how projects are managed—moving away from short-term, contract-based engagements towards more integrated and sustained collaborations—the adoption of Industry 5.0 technologies will likely remain limited. This highlights the need for a broader rethinking of the industry's operational paradigms, rather than merely tweaking existing models to fit current practices.

Interdisciplinary insights from sectors like manufacturing and logistics, which have successfully navigated similar technological shifts, offer potential strategies for overcoming the barriers identified in this study. However, the direct application of these strategies to construction must be approached with caution. While phased implementation and continuous stakeholder engagement have proven effective in other industries, the unique variability and complexity of construction projects may limit the transferability of these strategies. The reliance on industry-wide standards, particularly for technologies like Blockchain, presents another layer of complexity. The absence of standardized protocols in construction could exacerbate fragmentation rather than promote the desired integration, suggesting that solutions need to be tailored specifically to the industry's needs.

Furthermore, while interdisciplinary approaches can provide valuable insights, they must be critically assessed for their relevance and applicability to construction. The sector's distinct characteristics—such as its reliance on short-term, project-based work and diverse stakeholder environments—mean that strategies successful in other industries may not translate seamlessly. The study suggests that while strategies like phased implementation can offer some benefits, they must be carefully adapted to the specific context of construction. This adaptation process is itself complex and requires a deep understanding of the industry's unique challenges and a willingness to experiment with new approaches that may not have been tested elsewhere.

The study's call for a holistic approach to overcoming the barriers to Industry 5.0 adoption, integrating technological innovation with organizational change, policy interventions, and cultural transformation, also warrants critical reflection. While a holistic approach appears ideal, its practical implementation is fraught with challenges. Coordinating efforts across these diverse fronts—each with its own set of complexities and resistances—may prove difficult in an industry as fragmented and conservative as construction. Moreover, the assumption that policy interventions will drive widespread change overlooks the reality that such interventions are often inconsistent and slow to take effect, particularly in sectors where regulatory environments vary widely across regions and countries.

The cultural transformation necessary to support the successful adoption of Industry 5.0 technologies presents perhaps the most significant challenge of all. The construction industry's resistance to change is deeply rooted, and while change management strategies and continuous education could help, the study suggests that these measures alone may be insufficient. The industry's cultural preference for traditional practices is not just a surface-level issue but a fundamental aspect of its identity. Shifting this mindset may require more than just strategic interventions; it may necessitate a generational change in attitudes and practices, raising questions about whether the industry can achieve the necessary transformation within a timeframe that allows it to remain competitive globally.

Finally, while the study identifies several critical areas for future research and action, it is essential to approach these recommendations with caution. For instance, while further research into organizational culture in construction is undoubtedly necessary, the study suggests that achieving meaningful cultural change may be more challenging than anticipated. Similarly, while developing alternative models to predict technology adoption in fragmented, project-based industries seems necessary, such models must be designed with a deep understanding of the industry's specific challenges, avoiding the temptation to overgeneralize from other sectors. Additionally, policy reforms aimed at democratizing access to technology must be critically assessed for their long-term sustainability and their ability to drive meaningful change within smaller firms, which may continue to face structural barriers despite such efforts. As the construction industry navigates these complex dynamics, it becomes clear that the pathway forward is not straightforward and any progress will require a multi-faceted approach, combining rigorous academic inquiry with practical, industry-specific strategies as well as the ongoing reflection, adaptation, and collaboration among all stakeholders.

11 CONCLUSION

This systematic literature review (SLR) has underscored the transformative potential of Industry 5.0 technologies—such as IoT, AI, Digital Twins, Blockchain, and Collaborative Robots—in fundamentally reshaping supply chain integration within the construction industry. These technologies offer significant advancements in efficiency, transparency, and sustainability, directly addressing the long-standing inefficiencies that have hindered the sector’s growth and development.

As evidenced by our review, Industry 5.0 technologies stand poised to revolutionize how construction projects are managed and executed. IoT and AI, for example, streamline monitoring and decision-making processes by enhancing real-time data sharing and predictive analytics. Meanwhile, Digital Twins provide a robust, dynamic framework for optimizing construction workflows, enabling more accurate forecasting and resource management. Additionally, Blockchain technology plays a pivotal role in securing data integrity, fostering the trust and transparency that are essential for effective supply chain management in a highly fragmented industry like construction.

However, the road to fully realizing these benefits is not without challenges. The adoption of Industry 5.0 technologies is currently impeded by several significant barriers, including high implementation costs, a lack of standardized protocols, cybersecurity risks, and a shortage of skilled professionals. Furthermore, the construction industry’s deeply ingrained traditional practices and resistance to change further complicate the integration of these advanced technologies. Addressing these obstacles is not merely desirable but imperative if the construction sector is to unlock the full potential of Industry 5.0.

To overcome these challenges, a coordinated effort from all stakeholders is essential. Industry leaders must take the lead in developing strategic frameworks that support the gradual and coordinated integration of these technologies across the supply chain. Simultaneously, policymakers have a critical role in creating financial incentives, promoting standardization, and enforcing robust cybersecurity measures. Furthermore, targeted investments in workforce training are crucial to equip professionals with the skills needed to navigate the complexities of these new technologies.

As the construction industry stands on the cusp of a technological revolution, the adoption of Industry 5.0 technologies is not just an opportunity—it is a strategic necessity for future competitiveness and sustainability. The question that now emerges is not whether these technologies will be adopted, but how the industry will navigate the complexities and challenges of this transition. The path forward is fraught with uncertainty, but the decisions made today will shape the trajectory of the construction industry for decades to come. Will the industry rise to the challenge, embracing innovation and change to build a more resilient and forward-looking future? Only time will tell, but the imperative to act is clear.

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13 APPENDICES

13.1 DETAILED DESCRIPTION OF FIGURES

This appendix offers a detailed exploration of the figures presented in this study, providing a comprehensive analysis of their relevance to the investigation of Industry 5.0 technologies in enhancing Supply Chain Integration (SCI) within the construction sector. The figures not only depict the current state of the industry but also illuminate the transformative potential of technological innovation in addressing longstanding inefficiencies.

13.1.1 Figure 1: Recent Comparison of Productivity Growth by Industry (2010-2020)

- **Description:** This bar chart presents a comparison of annual productivity growth rates across three major industries—construction, manufacturing, and agriculture—over the decade from 2010 to 2020. The construction sector's productivity growth is notably sluggish at 1.0%, starkly contrasting with manufacturing's 2.5% and agriculture's 2.3%.
- **Analysis:** The pronounced disparity in productivity growth between construction and other sectors highlights a critical issue: the construction industry's chronic underperformance in leveraging technological advancements. Unlike manufacturing and agriculture, which have consistently integrated new technologies to enhance efficiency, the construction sector has remained entrenched in traditional practices. This stagnation can be attributed to several factors, including the industry's fragmented nature, resistance to change, and the complexity of construction projects, which often involve multiple stakeholders with conflicting interests. The data suggest that without a paradigm shift towards more advanced technological integration, the construction sector's productivity will continue to lag, potentially compromising its contribution to global economic growth.
- **Implications for the Study:** The productivity gap presented in this figure serves as a compelling rationale for exploring the role of Industry 5.0 technologies in the construction sector. This study seeks to understand how these technologies can bridge the productivity divide, fostering a more efficient and integrated approach to construction supply chains. By addressing this gap, the study contributes to the broader discourse on enhancing productivity and efficiency in sectors that have traditionally lagged in technological adoption.

13.1.2 Figure 2: Timeline of Industrial Revolutions and Technological Adoption in Construction

- **Description:** This timeline juxtaposes the progression of industrial revolutions with the pace of technological adoption within the construction sector. While industries have rapidly integrated innovations from each revolution, construction has been slower to embrace these changes, particularly in the context of the Fourth Industrial Revolution and the emerging Industry 5.0.
- **Analysis:** The timeline reveals a significant lag in the construction sector's adoption of key technological advancements introduced during successive industrial revolutions. This lag is not merely a delay in technology uptake but reflects deeper systemic

challenges within the industry. For instance, the complexity of construction projects, coupled with the sector's reliance on manual labor and traditional methods, has hindered the widespread adoption of digital and automated solutions. Furthermore, the decentralized nature of construction projects, involving numerous subcontractors and suppliers, complicates the integration of new technologies. As the global economy moves towards Industry 5.0, characterized by human-machine collaboration and advanced data analytics, the construction industry risks falling even further behind if it does not accelerate its adoption of these technologies.

- **Implications for the Study:** This timeline underscores the urgency of the study's focus on Industry 5.0. The construction sector's delayed response to previous industrial revolutions has contributed to its current inefficiencies. By exploring how Industry 5.0 technologies can be effectively integrated into construction practices, this study aims to offer actionable strategies for overcoming the industry's historical inertia and driving future growth.

13.1.3 Figure 3: Fragmented Construction Supply Chain

- **Description:** This diagram visually represents the fragmented nature of a typical construction supply chain, characterized by weak, siloed connections among key stakeholders, including the client, project manager, contractor, subcontractor, and supplier. The red dashed lines signify the fragile and inconsistent communication and collaboration that often plagues these relationships.
- **Analysis:** The figure highlights the pervasive issue of fragmentation within construction supply chains. This fragmentation is not only a source of inefficiency but also a significant risk factor that contributes to project delays, cost overruns, and quality issues. The lack of direct communication and coordination between stakeholders leads to frequent misunderstandings, misaligned objectives, and reactive rather than proactive management practices. Moreover, the reliance on traditional contractual arrangements exacerbates these problems, as each party tends to prioritize its own interests over the success of the project as a whole. This disjointed approach stands in stark contrast to the integrated models seen in more technologically advanced sectors, where collaboration and real-time data sharing are the norms.
- **Implications for the Study:** Addressing the fragmentation depicted in this figure is central to the study's objectives. By examining how Industry 5.0 technologies—such as IoT for real-time monitoring, Blockchain for secure transactions, and AI for predictive analytics—can be used to integrate these disconnected supply chain elements, the study aims to propose a new model for construction supply chain management that is more resilient, efficient, and collaborative.

13.1.4 Figure 4: Integrated Construction Supply Chain

- **Description:** In contrast to the previous figure, this diagram illustrates an integrated construction supply chain, characterized by strong, direct connections between stakeholders (client, project manager, contractor, subcontractor, and supplier). The green solid lines represent robust communication, collaboration, and information sharing across all parties.

- **Analysis:** This figure depicts the ideal state of a fully integrated supply chain, where each stakeholder is connected through seamless communication channels and aligned objectives. The integration of stakeholders is crucial in complex projects, where coordination and synchronization can significantly enhance project performance. The direct lines of communication eliminate bottlenecks and delays, while real-time data sharing enables more informed decision-making and proactive management. This model aligns closely with the principles of Industry 5.0, where advanced technologies enhance human collaboration and decision-making processes. Technologies such as Digital Twins, which provide a virtual replica of the project, and AI-driven analytics, which offer predictive insights, are instrumental in achieving this level of integration.
- **Implications for the Study:** The integrated model serves as a benchmark for what the construction industry can achieve through the adoption of Industry 5.0 technologies. This study will explore the practical steps needed to transition from the current fragmented state to this integrated model, focusing on the role of technology in facilitating this transformation. By doing so, the study aims to contribute to the development of a more efficient, collaborative, and forward-thinking construction industry.

13.1.5 Figure 5: SLR process followed

- **Description:** This PRISMA flow diagram provides an illustrative overview of the systematic literature review (SLR) process that this study follows. The diagram visually represents the key stages—Identification, Screening, Eligibility, and Inclusion—that guide the research methodology. Although this version of the PRISMA diagram does not contain specific data regarding the number of studies identified, screened, and included, it serves to outline the structured approach adopted for this study.
- **Analysis:** The inclusion of the PRISMA flow diagram in this appendix is intended to demonstrate the study's adherence to best practices in systematic literature review methodology. By following the PRISMA framework, the study ensures that the review process is systematic, transparent, and replicable. This approach is critical for minimizing bias and enhancing the rigor of the research. The diagram serves as a conceptual guide that emphasizes the importance of a methodical approach in synthesizing a diverse body of literature, particularly in a rapidly evolving field like Industry 5.0.
- **Implications for the Study:** While this illustrative PRISMA flow diagram outlines the process, the detailed, data-driven PRISMA diagram, which will include the exact numbers of papers screened, excluded, and included, will be presented in the subsequent sections of the methodology. This refined version will provide concrete evidence of the study's thoroughness and the rigor applied during the search and selection process. The eventual PRISMA results will validate the systematic nature of the research and underpin the reliability of the study's findings.

13.1.6 Figure 7: Temporal Distribution of the Collected Studies

Description: This figure illustrates the temporal distribution of the collected studies, showing the number of studies published each year between 2018 and 2024. The bar chart highlights the frequency of publications across these years, with notable peaks in 2022 and 2023.

Analysis: The temporal distribution reveals several key insights into the research landscape concerning Industry 5.0 technologies and their application in construction supply chains. The peaks observed in 2022 and 2023 suggest a growing interest and recognition of the importance of these technologies in recent years. This trend may be attributed to the increasing complexity and demands of modern construction projects, which necessitate more advanced and integrated technological solutions. The steady rise in publications leading up to these years indicates a maturation of the field, as researchers build upon earlier foundational work to explore more specific and applied aspects of Industry 5.0 in construction.

The dip observed in 2021 might reflect external factors, such as the global impact of the COVID-19 pandemic, which could have delayed research activities or publication processes. However, the rebound in 2022 and the sustained interest in 2023 indicate resilience and an accelerating momentum in this research area. This trend underscores the urgency and relevance of Industry 5.0 technologies as construction stakeholders seek to enhance supply chain integration, efficiency, and resilience in a post-pandemic world.

Implications for the Study: The temporal distribution of studies aligns with the study's objectives to explore current and emerging trends in Industry 5.0 applications within construction supply chains. The concentration of recent studies provides a rich foundation for understanding the latest advancements and challenges in the field, ensuring that the study's findings are grounded in the most current research. Additionally, the observed trends may inform the study's recommendations by highlighting the growing emphasis on integrating advanced technologies to address evolving industry needs.

13.1.7 Figure 8: Geographical Distribution of Studies

Description: This pie chart presents the geographical distribution of the studies included in the review, indicating the proportion of studies conducted in various countries. The chart highlights contributions from regions such as the USA, China, the UK, and others, with a significant portion labeled as "Others," representing various other countries.

Analysis: The geographical distribution of studies reveals a diverse global interest in the application of Industry 5.0 technologies within construction supply chains. The significant representation of studies from the USA, China, and the UK is indicative of these countries' leadership in technological innovation and research. These regions are known for their advanced construction industries, which are increasingly adopting digital and automated solutions to improve efficiency, reduce costs, and enhance supply chain integration.

However, the substantial portion of studies categorized under "Others" suggests that research is not confined to traditionally dominant regions. This diversity highlights the global relevance of Industry 5.0 technologies and suggests that countries across different continents are recognizing the need to modernize their construction supply chains. The inclusion of studies from countries like Greece, Pakistan, and Italy further demonstrates the widespread applicability of these technologies, even in regions that may not be traditionally associated with high-tech construction practices.

Implications for the Study: The geographical diversity of the studies reinforces the global applicability of the study's findings and recommendations. It suggests that the benefits of Industry 5.0 technologies can be realized across a wide range of economic, cultural, and industrial contexts. This global perspective is essential for developing strategies that are adaptable and scalable, ensuring that the study's conclusions are relevant to a broad audience. Furthermore, the study can draw on the experiences and lessons learned from different regions to provide a more comprehensive understanding of the challenges and opportunities associated with implementing these technologies.

13.1.8 Figure 9: Distribution of Study Designs

Description: This bar chart displays the distribution of different study designs among the reviewed papers, including categories such as Review, Systematic Literature Review, Survey, Case Study and Review, Short Communication, and Concept Paper.

Analysis: The distribution of study designs reveals the methodological approaches employed in researching Industry 5.0 technologies within construction supply chains. The prominence of Review and Systematic Literature Review studies suggests that the field is still in a phase of conceptual exploration and synthesis. These studies play a crucial role in mapping the current state of knowledge, identifying gaps, and setting the stage for more empirical research. The presence of Survey and Case Study designs indicates that researchers are beginning to apply these concepts in real-world contexts, gathering data from industry practitioners and analysing specific cases to validate theoretical models.

The relatively lower number of Short Communication and Concept Paper studies suggests that the field is less focused on speculative or preliminary ideas at this stage. Instead, the emphasis is on consolidating existing knowledge and providing comprehensive reviews that can inform future research directions. The diversity of study designs also highlights the interdisciplinary nature of this research area, as it draws on methodologies from fields such as engineering, information technology, and management.

Implications for the Study: The distribution of study designs informs the study's approach by highlighting the importance of integrating different methodological perspectives. The prevalence of reviews suggests that there is a solid foundation of secondary research, which the study can build upon to develop a more detailed and empirical analysis. Additionally, the presence of case studies and surveys provides valuable data that can be used to ground the study's findings in practical, real-world scenarios. The study can leverage these diverse methodologies to offer a comprehensive and nuanced understanding of how Industry 5.0 technologies are transforming construction supply chains.

13.2 DETAILED INFORMATION ABOUT INDUSTRY 5.0 TECHNOLOGIES

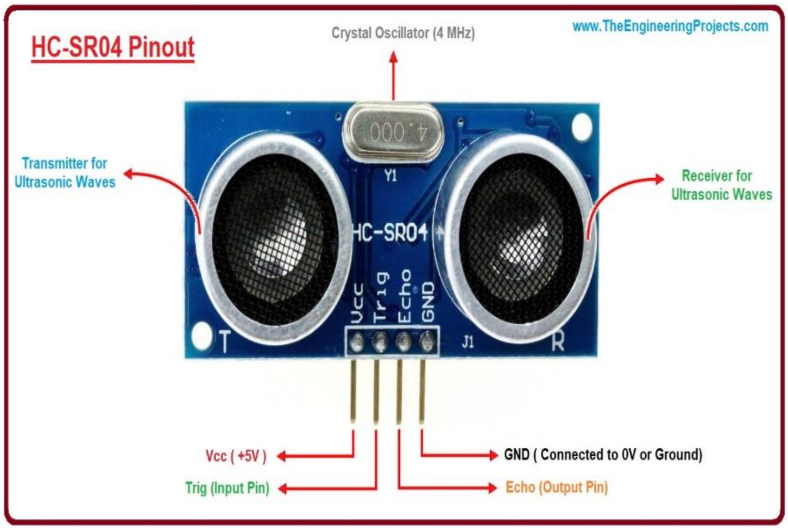
This appendix provides a comprehensive exploration of the key Industry 5.0 technologies that are driving advancements in Supply Chain Integration (SCI) within the construction sector. It details the definitions, technical specifications, real-world examples, and economic considerations of the critical technologies mentioned in this report:

13.2.1 Internet of Things (IoT)

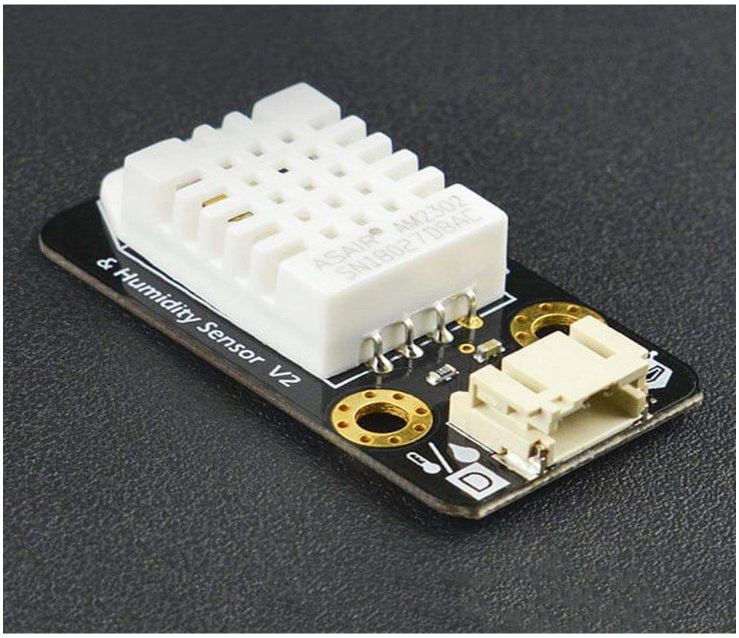
- **Definition:** The Internet of Things (IoT) connects physical devices through embedded sensors, software, and communication technologies, enabling data collection and exchange over the internet. This networked environment facilitates real-time monitoring, decision-making, and automation in Industry 5.0 settings (Ashton, 2009).

- **Technical Details:**
  - **Ultrasonic Sensors:** Operating at frequencies above 20 kHz, these sensors measure distance by calculating the time delay between the emission and reception of ultrasonic waves. They are crucial in applications like level measurement in tanks and collision avoidance systems in autonomous vehicles.
  - **Temperature Sensors (NTC Thermistors):** These resistive devices change resistance with temperature, offering precise temperature monitoring in industrial processes. They are commonly used in HVAC systems, industrial ovens, and manufacturing lines.
  - **Vibration Sensors (Piezoelectric Accelerometers):** These sensors detect mechanical vibrations and convert them into electrical signals. In manufacturing, they are used for condition monitoring of machinery, helping to predict and prevent equipment failures.

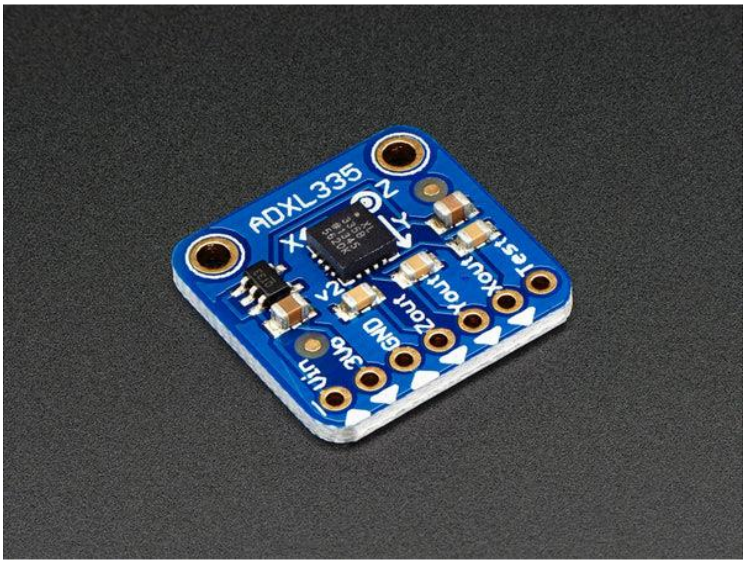
- **Examples of Devices:**
  - **HC-SR04 Ultrasonic Sensor:** A widely used sensor in robotics and automation for obstacle detection, priced between $3 and $5.



  - **DHT22 Temperature and Humidity Sensor:** Provides accurate measurements for environmental monitoring, costing around $10 to $15.



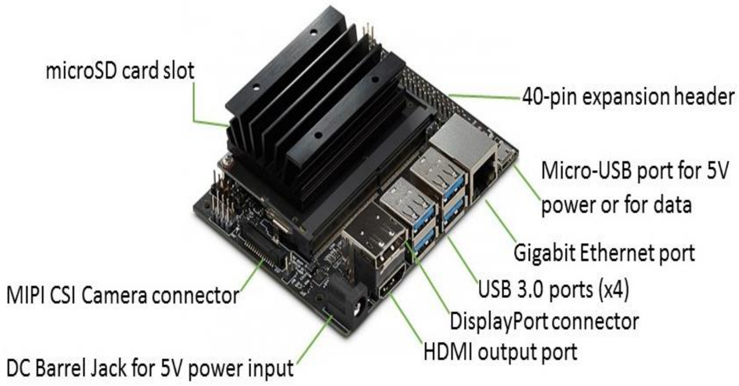
- **ADXL335 Vibration Sensor:** Used in predictive maintenance applications to monitor machinery health, priced at approximately $20 to $30.



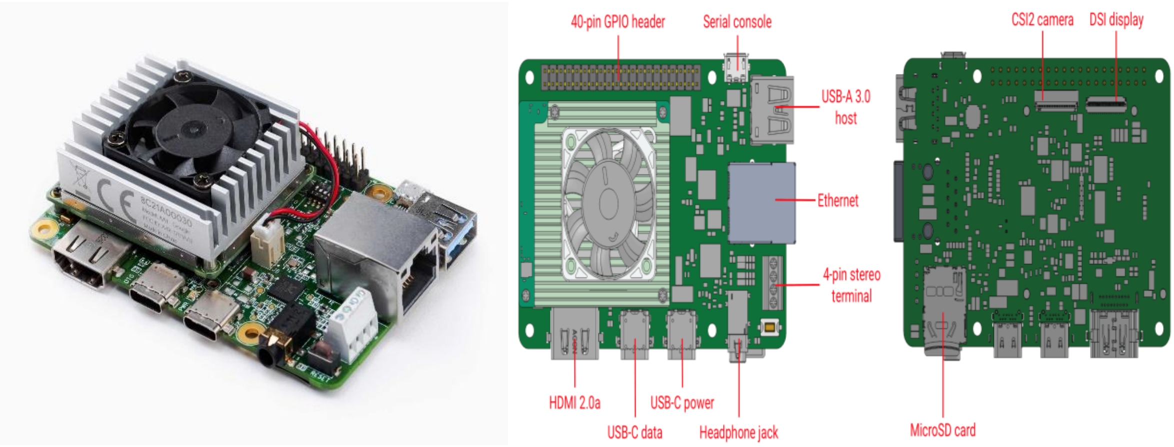
- **Real-World Application:**
  - **Smart Factory Implementation:** Siemens uses IoT sensors extensively in their "Amberg Electronics Plant," where over 75% of the production process is automated, resulting in nearly zero defects.
- **Other Details:**
  - **Market Growth:** The IoT market is projected to grow to $1.6 trillion by 2025, with the Industrial IoT (IIoT) segment being a major driver (Grand View Research, 2021).
  - **Cost Considerations:** Implementing IoT across a large industrial facility can range from $50,000 to over $1 million, depending on the scope and scale of the deployment.

13.2.2 Artificial Intelligence (AI)

- **Definition:** Artificial Intelligence (AI) refers to systems that simulate human intelligence to perform tasks such as learning, reasoning, and problem-solving. In Industry 5.0, AI enhances decision-making, optimizes operations, and enables predictive maintenance (Russell & Norvig, 2020).
- **Technical Details:**
    - **Machine Learning (ML):** ML algorithms, particularly those based on neural networks like Convolutional Neural Networks (CNNs), are used for image recognition, predictive maintenance, and quality control in manufacturing.
    - **Natural Language Processing (NLP):** NLP enables machines to understand and respond to human language, facilitating more intuitive human-machine interactions in collaborative settings.
    - **Reinforcement Learning:** A type of ML where agents learn to make decisions by receiving rewards or penalties, applied in robotics and autonomous systems.
- **Examples of Devices:**
    - **NVIDIA Jetson Nano:** A popular platform for deploying AI at the edge, used in applications ranging from autonomous vehicles to smart cameras, priced at around $99.



    - **Google Coral Dev Board:** This AI development board is used for high-performance edge applications, particularly in image processing and object detection, priced at approximately $130.



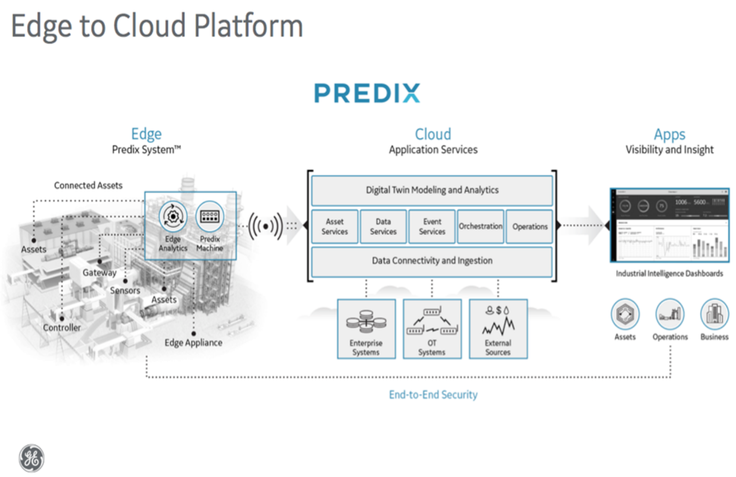
- **Cobots Powered by AI:** For example, the UR3e from Universal Robots, a collaborative robot capable of performing delicate tasks with high precision, priced between $45,000 and $55,000.

- **Real-World Application:**
  - **Automated Quality Control in Manufacturing:** BMW uses AI-driven visual inspection systems to detect defects in car body components, reducing error rates by 85%.
- **Other Details:**
  - **Market Projections:** The global AI market is expected to grow to $190.61 billion by 2025, with AI in manufacturing projected to save up to 30% in operational costs (Markets and Markets, 2020).
  - **Implementation Costs:** AI implementation, particularly in large-scale manufacturing, can range from $500,000 to several million dollars, depending on the complexity and scope of the project.

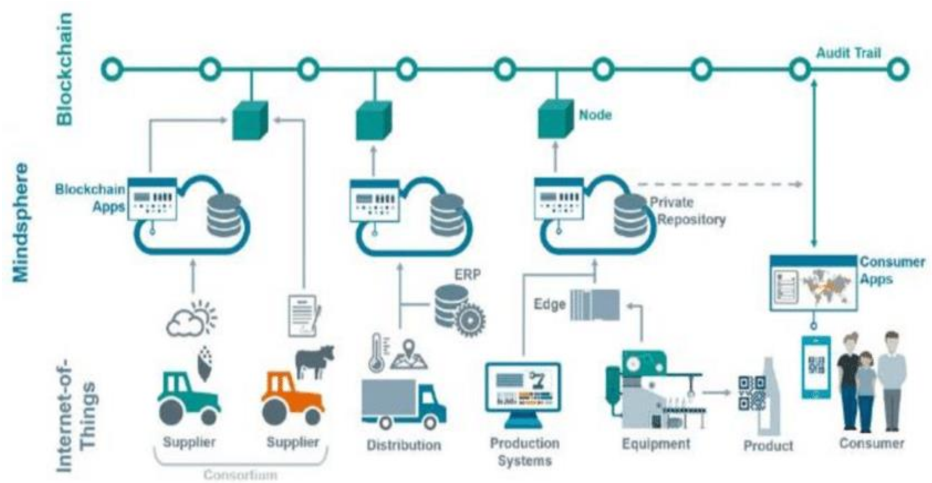
13.2.3 Digital Twins

- **Definition:** Digital Twins are virtual replicas of physical systems, processes, or products that mirror real-time conditions and enable predictive analysis and optimization. They are crucial in Industry 5.0 for enhancing operational efficiency and enabling proactive maintenance (Tao et al., 2019).
- **Technical Details:**
  - **Integration with IoT:** Digital Twins rely on IoT sensors to provide real-time data, which is then processed using AI to simulate different scenarios and predict outcomes.
  - **3D Simulation:** Advanced Digital Twins utilize 3D models and simulations to visualize complex processes, making it easier to identify inefficiencies and optimize operations.
  - **Predictive Analytics:** These tools forecast future conditions based on current data trends, helping businesses to anticipate and mitigate risks.

- **Examples of Applications:**
    - **GE Predix Platform:** Used to manage and optimize the performance of industrial assets such as jet engines and wind turbines. This platform enables real-time monitoring and predictive maintenance, significantly reducing downtime and operational costs.



    - **Siemens MindSphere:** A cloud-based platform that uses Digital Twins for product lifecycle management, allowing manufacturers to optimize design, production, and service processes.

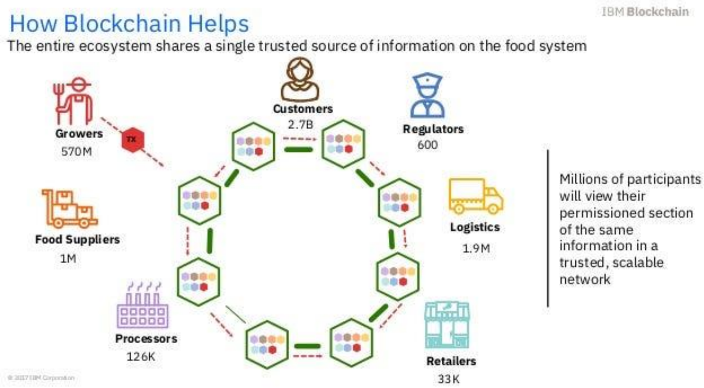


- **Real-World Application:**
    - **Wind Farm Management:** General Electric's Digital Twin technology is used to manage wind farms, improving energy output by 5% and reducing maintenance costs by 25%.
- **Other Details:**
    - **Market Trends:** The Digital Twin market is forecasted to reach $48.2 billion by 2026, driven by its application in manufacturing, healthcare, and smart cities (Fortune Business Insights, 2021).

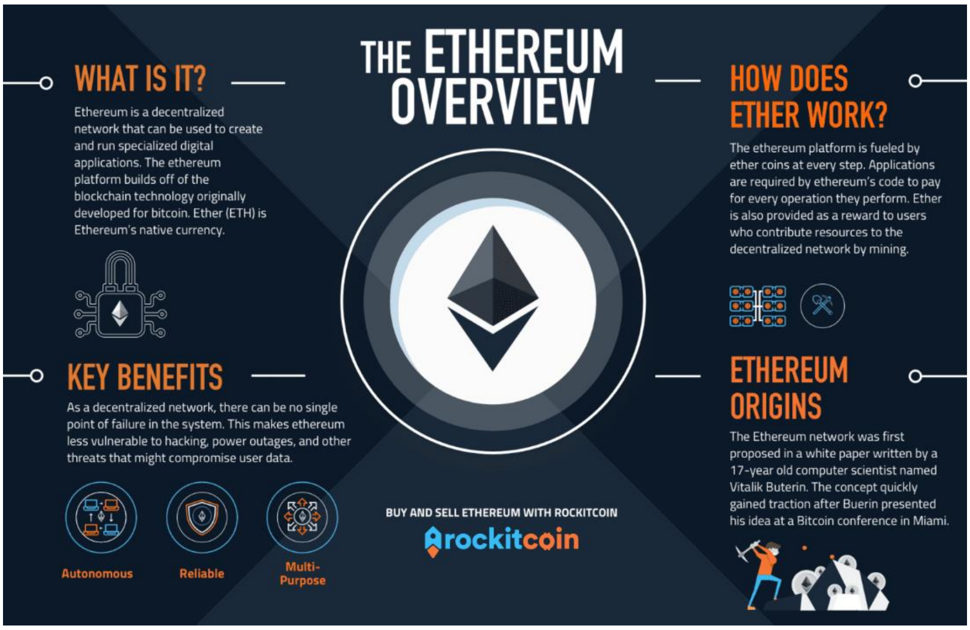
- **Cost Implications:** Developing a comprehensive Digital Twin can cost upwards of $500,000, depending on the complexity of the system and the extent of data integration required.

13.2.4 Blockchain

- **Definition:** Blockchain is a decentralized ledger technology that securely records transactions across multiple systems, ensuring transparency and immutability. In Industry 5.0, Blockchain is used to streamline supply chains, enhance security, and enable trustless transactions (Tapscott & Tapscott, 2016).
- **Technical Details:**
    - **Decentralized Ledger:** Blockchain operates without a central authority, distributing data across a network of nodes. Each block in the chain contains a cryptographic hash of the previous block, ensuring that records cannot be altered retroactively.
    - **Smart Contracts:** These are self-executing contracts with the terms directly written into code, enabling automated and enforceable agreements without intermediaries.
    - **Consensus Mechanisms:** Proof of Work (PoW) and Proof of Stake (PoS) are common consensus algorithms used in Blockchain to validate transactions and secure the network.
- **Examples of Applications:**
    - **IBM Food Trust:** This Blockchain platform enhances the traceability of food products, reducing the time needed to trace items from days to seconds, which helps prevent fraud and contamination in the food supply chain.



    - **Ethereum Platform:** Supports decentralized applications (DApps) and smart contracts, facilitating a wide range of applications from supply chain tracking to decentralized finance (DeFi).



- **Real-World Application:**
  - **Supply Chain Management in Diamond Industry:** De Beers uses Blockchain to track diamonds from mine to retail, ensuring the authenticity and ethical sourcing of each stone.

Polygon
The jewelry industry's most active online community & trading network
WWW.POLYGON.NET

JEWELRY BUSINESS INSIGHT

De Beers is Embracing Diamond Tracking Based on Blockchain Technology

www.Polygon.net

Nathan Munn

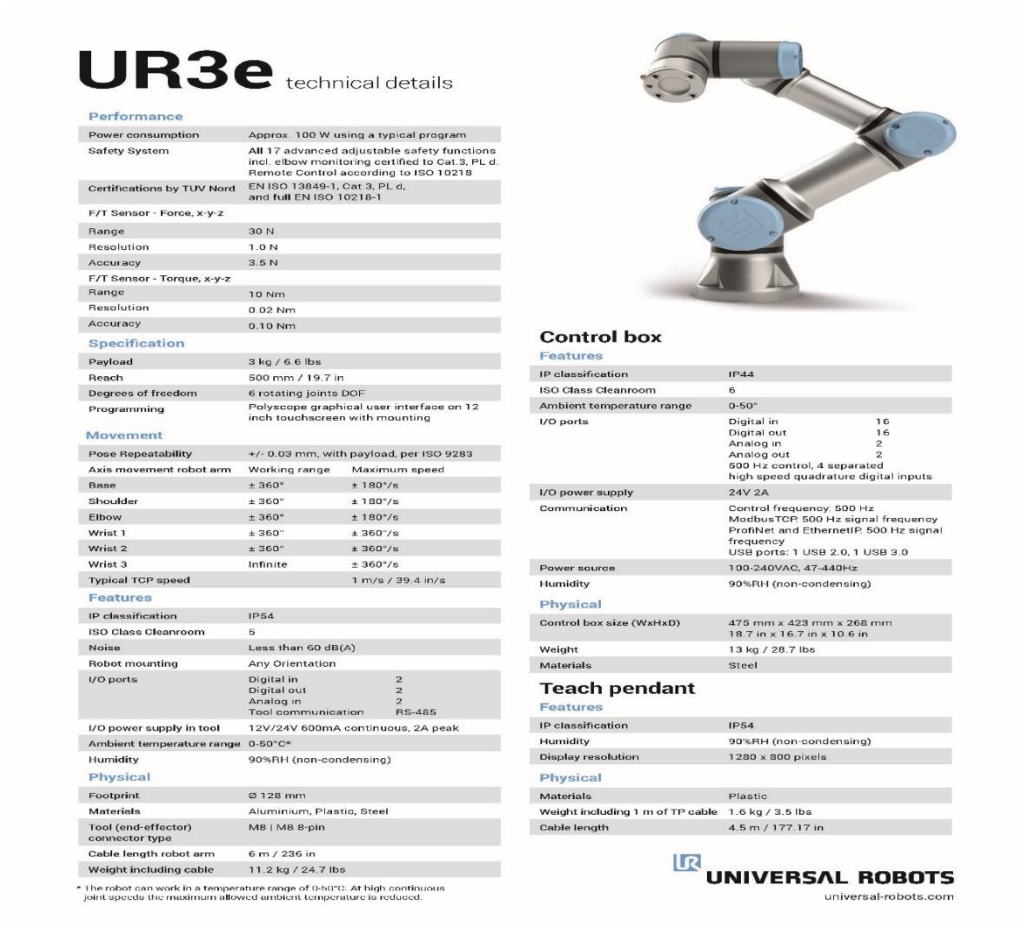
Dec. 11, 2017 POLYGON.NET

- **Other Details:**
    - **Market Projections:** The Blockchain market is anticipated to grow to $163.83 billion by 2029, with significant adoption in finance, supply chain, and healthcare (Fortune Business Insights, 2022).
    - **Cost Considerations:** Implementing Blockchain in a supply chain context varies significantly depending on the scale and complexity of the system. For instance, integrating Blockchain into a medium-sized enterprise's supply chain can cost between $150,000 and $300,000, covering software development, infrastructure, and deployment. Operational costs, including transaction fees and ongoing maintenance, also need to be factored in, which can range from $20,000 to $50,000 annually.

13.2.5 Othe technologies mentioned

13.2.5.1 Collaborative Robots (Cobots)

- **Definition:** Collaborative Robots, or Cobots, are robots designed to work alongside human operators in a shared workspace, enhancing productivity, safety, and flexibility. Unlike traditional industrial robots, which often operate in isolation due to safety concerns, Cobots are built with sensors and software that enable safe interaction with human workers (Peshkin & Colgate, 1999).
- **Technical Details:**
    - **Safety Features:** Cobots are equipped with advanced sensors such as force-limiting sensors, which stop the robot's motion when it encounters resistance or a collision, ensuring the safety of nearby human workers.
    - **AI Integration:** Cobots leverage AI to learn from human actions and adapt to varying tasks, making them highly flexible. Machine learning algorithms enable Cobots to improve their performance over time and adjust to new tasks with minimal reprogramming.
    - **Ease of Deployment:** Cobots are designed to be user-friendly, often requiring minimal programming skills. Many Cobots are equipped with intuitive interfaces that allow operators to teach them new tasks through demonstration rather than complex coding.
- **Examples of Cobots:**
    - **Universal Robots UR5:** A versatile and lightweight Cobot, the UR5 is commonly used for tasks such as pick-and-place, assembly, and quality inspection. It supports payloads of up to 5 kg and is priced between $35,000 and $45,000.



UR3e technical details

Performance

Power consumption	Approx. 100 W using a typical program	
Safety System	All 17 advanced adjustable safety functions incl. elbow monitoring certified to Cat.3, PL d. Remote Control according to ISO 10218	
Certifications by TUV Nord	EN ISO 13849-1, Cat.3, PL d, and full EN ISO 10218-1	
F/T Sensor - Force, x-y-z		
Range	30 N	
Resolution	1.0 N	
Accuracy	3.5 N	
F/T Sensor - Torque, x-y-z		
Range	10 Nm	
Resolution	0.02 Nm	
Accuracy	0.10 Nm	

Specification

Payload	3 kg / 6.6 lbs
Reach	500 mm / 19.7 in
Degrees of freedom	6 rotating joints DOF
Programming	Polyscope graphical user interface on 12 inch touchscreen with mounting

Movement

Pose Repeatability	+/- 0.03 mm, with payload, per ISO 9283	
Axis movement robot arm	Working range	Maximum speed
Base	± 360°	± 180°/s
Shoulder	± 360°	± 180°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 360°/s
Wrist 2	± 360°	± 360°/s
Wrist 3	Infinite	± 360°/s
Typical TCP speed		1 m/s / 39.4 in/s

Features

IP classification	IP54
ISO Class Cleanroom	5
Noise	Less than 60 dB(A)
Robot mounting	Any Orientation
I/O ports	Digital in 2 Digital out 2 Analog in 2 Tool communication RS-485
I/O power supply in tool	12V/24V 600mA continuous, 2A peak
Ambient temperature range	0-50°C*
Humidity	90%RH (non-condensing)

Physical

Footprint	Ø 128 mm
Materials	Aluminium, Plastic, Steel
Tool (end-effector) connector type	M8 | M8 8-pin
Cable length robot arm	6 m / 236 in
Weight including cable	11.2 kg / 24.7 lbs

* The robot can work in a temperature range of 0-50°C. At high continuous joint speeds the maximum allowed ambient temperature is reduced.

Control box

Features

IP classification	IP44
ISO Class Cleanroom	6
Ambient temperature range	0-50°
I/O ports	Digital in 16 Digital out 16 Analog in 2 Analog out 2 500 Hz control, 4 separated high speed quadrature digital inputs
I/O power supply	24V 2A
Communication	Control frequency: 500 Hz ModbusTCP: 500 Hz signal frequency ProfiNet and EthernetIP: 500 Hz signal frequency USB ports: 1 USB 2.0, 1 USB 3.0
Power source	100-240VAC, 47-440Hz
Humidity	90%RH (non-condensing)

Physical

Control box size (WxHxD)	475 mm x 423 mm x 268 mm 18.7 in x 16.7 in x 10.6 in
Weight	13 kg / 28.7 lbs
Materials	Steel

Teach pendant

Features

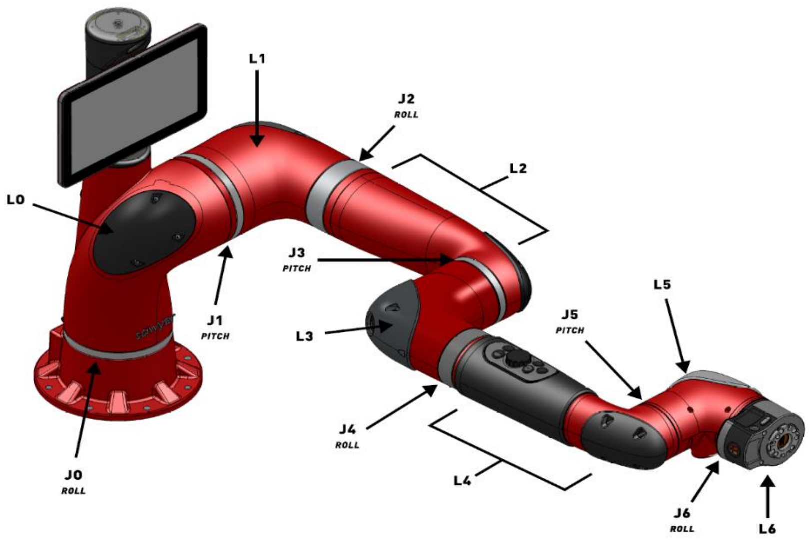
IP classification	IP54
Humidity	90%RH (non-condensing)
Display resolution	1280 x 800 pixels

Physical

Materials	Plastic
Weight including 1 m of TP cable	1.6 kg / 3.5 lbs
Cable length	4.5 m / 177.17 in

UNIVERSAL ROBOTS
universal-robots.com

- **Rethink Robotics' Sawyer:** Known for its precision and adaptability, Sawyer is equipped with embedded vision and is designed for high-precision tasks in electronics and consumer goods manufacturing. It is priced around $29,000.



	Rethink Robotics - Sawyer
	
Number of Axes	7-axis arm
Payload	4 kg (8.8 lbs)
Reach	1,026 mm (40.4 in)
Weight	19 kg (42 lbs)
Speed	1m/s w/o payload; 0.6m/s with
Repeatability	+/- 0,1 mm (0.0039 in)
Targeted Applications	Machine Tending Circuit board testing Material handling
Vision & Sensors	1 arm integrated camera, integrated force sensors, front camera for human detection

- **Real-World Application:**
  - **Automotive Assembly:** Ford Motor Company utilizes Cobots to assist workers in tightening bolts, applying adhesives, and performing other tasks that require precision. This collaboration between human workers and Cobots has increased production efficiency by 20%.
- **Other Details:**
  - **Market Growth:** The global Cobot market is expected to grow from $1.2 billion in 2020 to $8.7 billion by 2027, driven by increasing demand for automation in small and medium-sized enterprises (Allied Market Research, 2021).
  - **Cost-Benefit Analysis:** Cobots typically offer a return on investment (ROI) within 12 to 18 months due to their ability to enhance productivity and reduce operational costs. For example, a Cobot deployment that costs $45,000 can

result in annual savings of $30,000 to $50,000 through increased efficiency and reduced labour costs.

13.2.5.2 Building Information Modelling (BIM)

- **Definition:** Building Information Modelling (BIM) is a digital representation of the physical and functional characteristics of a building or infrastructure. BIM serves as a shared knowledge resource, facilitating decision-making throughout the entire lifecycle of a project—from design and construction to operation and maintenance (Eastman et al., 2011).

- **Technical Details:**

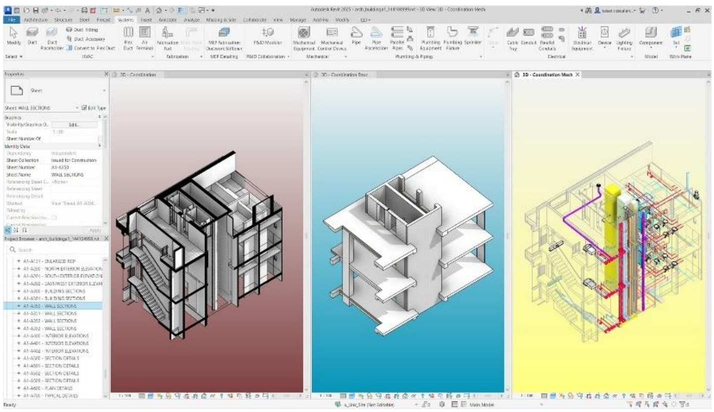
  - **3D Modelling:** BIM extends beyond traditional 2D drawings by integrating 3D models that provide detailed visualizations of the structure. These models are often rich with data, including geometrical and spatial information, material specifications, and functional details.

  - **Data Integration:** BIM integrates various data sources and stakeholders into a single digital model. It allows for the incorporation of data from structural engineering, mechanical, electrical, and plumbing (MEP) systems, and other disciplines, ensuring that all aspects of a project are synchronized and accessible in one platform.

  - **Interoperability and Standards:** BIM relies on interoperable software platforms that follow international standards like the Industry Foundation Classes (IFC) and BIM Level 2 and 3 frameworks, enabling seamless collaboration across different software and stakeholders.

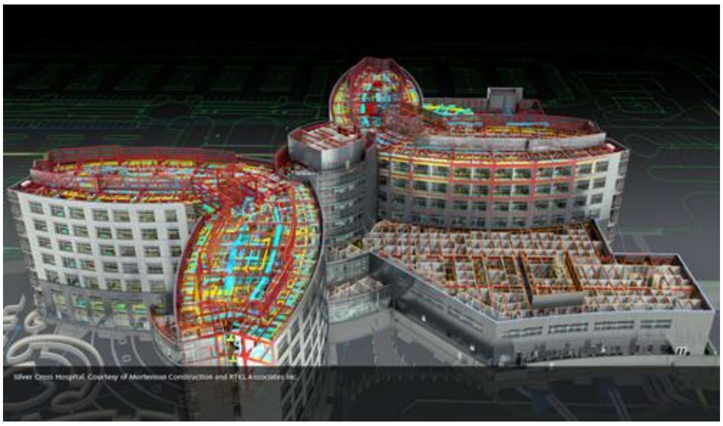
- **Examples of BIM Software:**

  - **Autodesk Revit:** One of the most widely used BIM tools, Revit allows users to create detailed 3D models, manage building data, and simulate real-world performance. It is extensively used in architecture, engineering, and construction (AEC) industries.

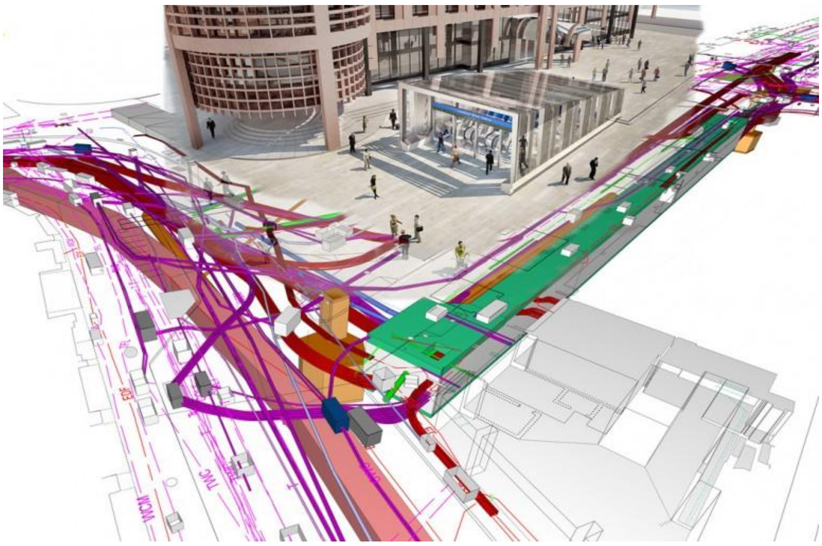


  - **Bentley Systems' MicroStation:** Known for its powerful modeling capabilities, MicroStation supports BIM workflows and is used in infrastructure projects, including roads, bridges, and rail systems.

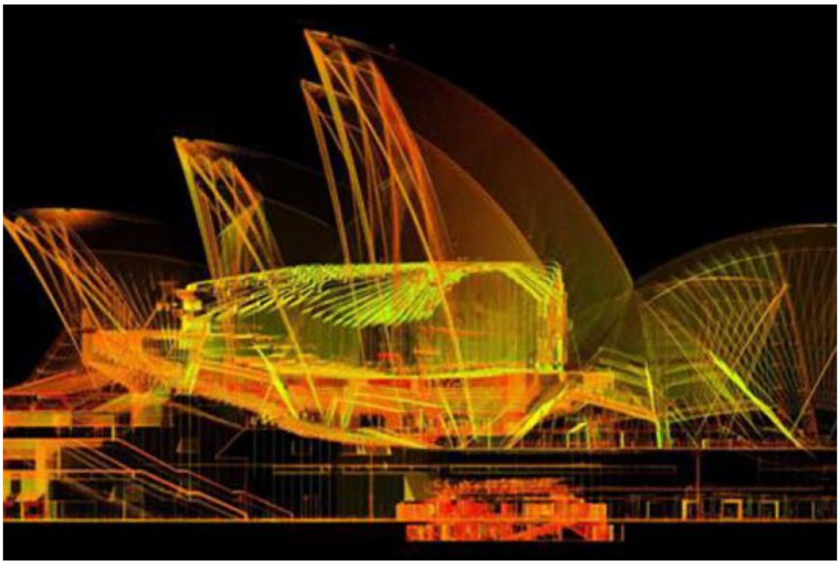
- **Navisworks:** Often used in conjunction with other BIM tools, Navisworks enables project review, 4D simulation (time), and 5D simulation (cost) analysis, helping teams visualize and manage the construction process more effectively.



- **Real-World Application:**
  - **Crossrail Project in London:** One of the largest and most complex BIM implementations, the Crossrail project used BIM to integrate design and construction data across multiple contractors and stakeholders. This enabled better coordination, reduced errors, and streamlined project delivery, resulting in a significant reduction in project delays and cost overruns.



- **Sydney Opera House Renovation:** BIM was employed to manage the renovation of this iconic structure. The digital model helped in preserving the historical integrity of the building while allowing for the integration of modern systems and technologies, enhancing the building's performance and sustainability.



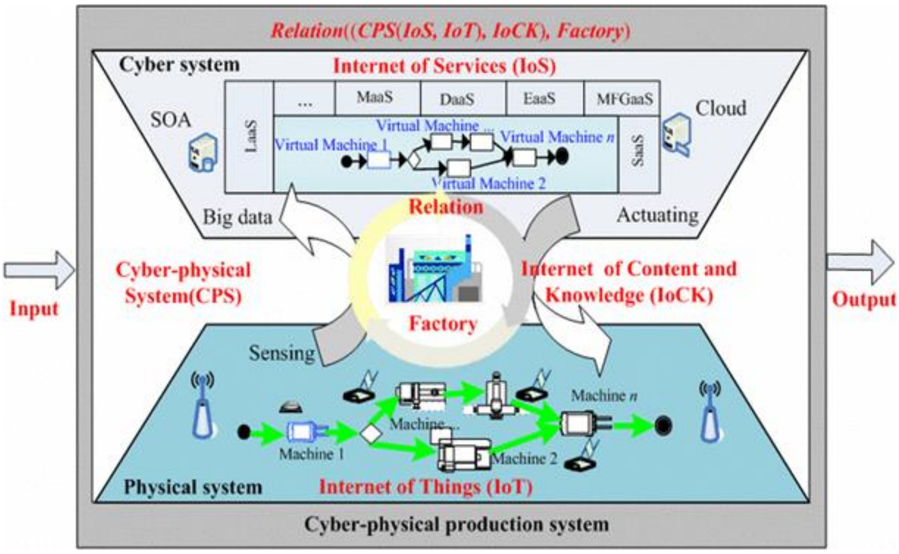
- **Other Details:**
  - **Market Trends:** The global BIM market is expected to grow from $5.2 billion in 2021 to $10.7 billion by 2026, driven by increasing adoption in the construction and infrastructure sectors (MarketsandMarkets, 2021).
  - **Cost Implications:** Implementing BIM can lead to cost savings of 20-30% due to reduced errors, improved coordination, and enhanced efficiency in project management (McGraw Hill Construction, 2014). However, the initial investment in BIM software and training can range from $50,000 to $200,000 for medium to large-sized projects.
  - **Legal and Regulatory Considerations:** Several countries, including the UK and Singapore, have mandated the use of BIM for public construction projects, underscoring its importance in modern construction practices. These mandates are often linked to achieving sustainability goals, reducing carbon footprints, and ensuring long-term asset management efficiency.

13.2.5.3 Cyber-Physical Systems (CPS)

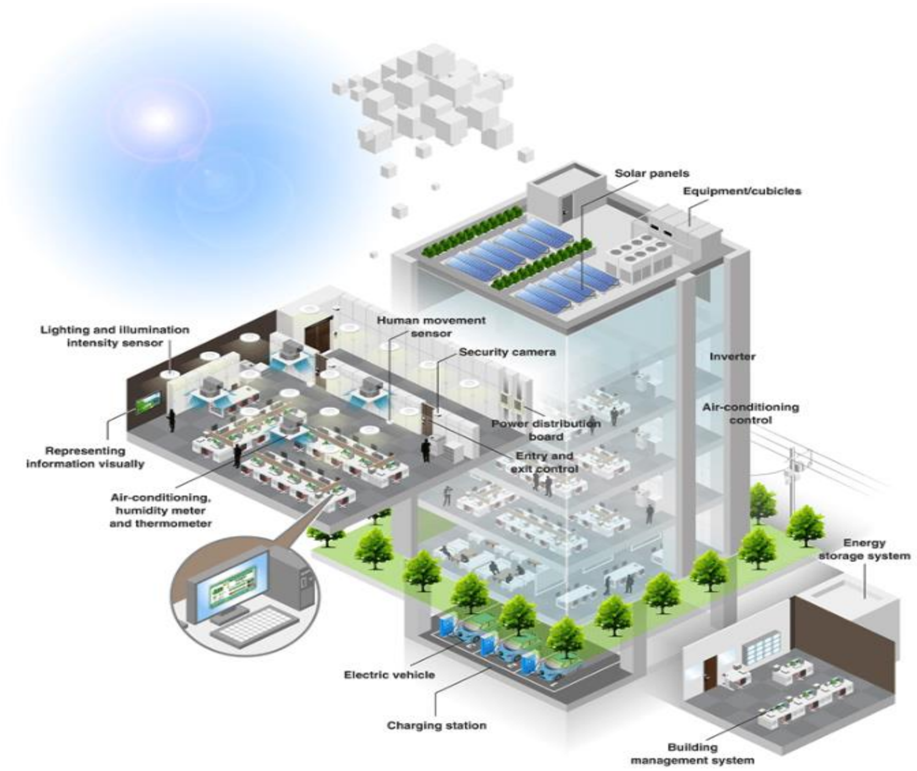
- **Definition:** Cyber-Physical Systems (CPS) are integrations of computation, networking, and physical processes. In a CPS, embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (Lee, 2008). CPS forms the backbone of Industry 5.0, enabling the seamless interaction between digital systems and physical infrastructure.

- **Technical Details:**
  - **Embedded Systems:** CPS relies heavily on embedded systems, which are dedicated computer systems integrated into larger mechanical or electrical systems. These systems perform real-time monitoring and control tasks, often in environments where timing and reliability are critical.
  - **Sensors and Actuators:** Sensors gather data from the physical environment, such as temperature, pressure, and motion, and feed this information into computational systems. Actuators then perform physical actions based on the computational feedback, like adjusting machinery, triggering alarms, or altering production processes.
  - **Real-Time Data Processing:** CPS is characterized by its ability to process data in real-time, which is essential for applications such as automated manufacturing, smart grids, and autonomous vehicles. This real-time capability ensures that physical systems can respond immediately to changes in their environment, enhancing efficiency and safety.
  - **Interoperability and Networking:** CPS involves the integration of various subsystems that must communicate and function together seamlessly. Networking technologies such as wireless sensor networks (WSNs) and Internet of Things (IoT) platforms are critical in enabling this interoperability, ensuring that data flows freely between components and that systems can be remotely monitored and controlled.
- **Examples of CPS in Use:**
  - **Smart Grids:** In energy management, CPS enables the creation of smart grids, where electricity generation, distribution, and consumption are monitored and controlled in real-time. This results in more efficient energy use, reduced operational costs, and enhanced grid reliability.

  - **Automated Manufacturing:** In the automotive industry, CPS is used to integrate production lines with digital twins and IoT sensors, allowing for automated monitoring and control of the manufacturing process. This integration leads to increased precision, reduced waste, and higher production throughput.



- **Smart Buildings:** CPS is applied in smart buildings where HVAC systems, lighting, and security are managed through a central control system that interacts with physical infrastructure. This not only enhances energy efficiency but also improves occupant comfort and safety.



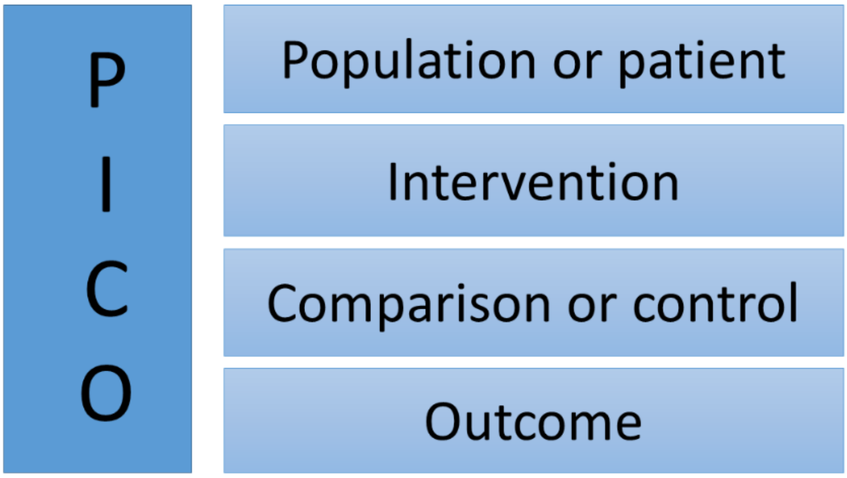
- **Real-World Application:**
  - **Industry 4.0 Production Systems:** Companies like Siemens and Bosch have implemented CPS in their manufacturing plants to create highly automated and adaptable production environments. These CPS-enabled factories can quickly respond to changes in demand, optimize production schedules, and reduce downtime through predictive maintenance.
  - **Autonomous Vehicles:** CPS is central to the development of autonomous vehicles. By integrating sensors, actuators, and real-time processing, vehicles

can navigate and respond to their environments without human intervention, making decisions on speed, direction, and obstacle avoidance.

- **Other Details:**
  - **Market Trends:** The CPS market is growing rapidly, with projections estimating it will reach $106.2 billion by 2026, driven by advancements in IoT, artificial intelligence, and 5G technologies (MarketsandMarkets, 2021).
  - **Challenges and Considerations:** Implementing CPS comes with challenges, including ensuring cybersecurity, maintaining interoperability across diverse systems, and managing the complexity of integrating physical and computational components. Additionally, the cost of developing and maintaining CPS can be high, particularly in sectors requiring high reliability and real-time performance.
  - **Cybersecurity:** As CPS are deeply integrated with physical systems, any breach or malfunction could have severe consequences, making cybersecurity a critical consideration. Protecting CPS against cyber threats involves implementing robust encryption, continuous monitoring, and regular updates to safeguard against vulnerabilities.

13.3 Detailed Application of the PICO Framework to Develop Research Questions

This appendix provides a thorough breakdown of how the PICO framework was applied to develop the research questions for this study. The PICO framework, originally developed for clinical research, has been adapted to suit the context of this systematic literature review (SLR) by focusing on the integration of Industry 5.0 technologies within the construction sector's supply chains. Each element of the PICO framework—Population, Intervention, Comparison, and Outcome—was carefully considered to ensure that the research questions are comprehensive, relevant, and aligned with the study's objectives.



13.3.1 Population (P): Construction Industry Supply Chains

- **Contextualization:** The "Population" in this framework refers to the specific setting or subject group under investigation. For this study, the population is defined as the construction industry's supply chains. The construction sector was chosen due to its pivotal role in global infrastructure and its well-documented challenges related to fragmented supply chains and low productivity (McKinsey & Company, 2017).

- **Rationale:** Focusing on the construction sector allows the study to address the specific needs and characteristics of this industry, such as its complex, project-based nature and the diversity of stakeholders involved. By defining the population this way, the research questions can be precisely tailored to explore how Industry 5.0 technologies might overcome these industry-specific challenges.

13.3.2 Intervention (I): Adoption of Industry 5.0 Technologies

- **Contextualization:** The "Intervention" refers to the main action, strategy, or technology being investigated. In this study, the intervention comprises the adoption of Industry 5.0 technologies, specifically the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, Blockchain, and Collaborative Robots (Cobots).

- **Rationale:** Each of these technologies represents a significant advancement that could enhance supply chain integration by addressing issues such as real-time data sharing, predictive maintenance, transparency, and collaboration (Demir et al., 2020; Özdemir & Hekim, 2018). The inclusion of multiple technologies allows the study to assess both individual and combined effects on supply chain integration.

13.3.3 Comparison (C): Implicit Comparison with Current Fragmented Supply Chains

- **Contextualization:** While the "Comparison" component traditionally involves a direct alternative to the intervention, in this study, the comparison is implicit. The study contrasts the potential benefits of Industry 5.0 technologies with the current state of fragmented and inefficient supply chains in the construction sector.

- **Rationale:** By comparing the envisioned integrated supply chains enabled by Industry 5.0 technologies with the existing fragmented models, the research questions aim to highlight the improvements these technologies could bring and identify the barriers that might impede their adoption.

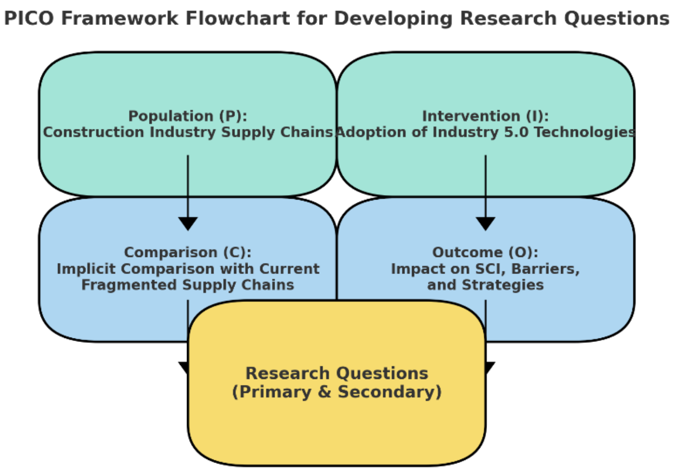
13.3.4 Outcome (O): Impact on Supply Chain Integration, Identification of Barriers, and Strategies for Overcoming Them

- **Contextualization:** The "Outcome" refers to the expected results or impacts of the intervention. In this study, the primary outcomes include the degree to which Industry 5.0 technologies can enhance supply chain integration, the identification of barriers to their adoption, and the development of strategies to overcome these barriers.

- **Rationale:** Focusing on these outcomes ensures that the research questions are not only theoretical but also practical, offering insights that could directly inform industry practices and future research. The emphasis on barriers and strategies is particularly critical, given the construction sector's historical resistance to technological change (Oesterreich & Teuteberg, 2016).

13.3.5 Results of Applying the PICO Framework

The application of the PICO framework resulted in the formulation of three central research questions that guide this study:



1. **Primary Research Question:**
    - *How do key Industry 5.0 technologies, specifically IoT, AI, Digital Twins, Blockchain, and Cobots, impact supply chain integration in the construction industry?*
    - **Derived from:** Population (Construction Industry Supply Chains) + Intervention (Adoption of Industry 5.0 Technologies) + Outcome (Impact on Supply Chain Integration).
2. **Secondary Research Question 1:**
    - *What are the barriers to the adoption of these technologies within the construction industry's supply chain?*
    - **Derived from:** Population (Construction Industry Supply Chains) + Intervention (Adoption of Industry 5.0 Technologies) + Outcome (Identification of Barriers).
3. **Secondary Research Question 2:**
    - *What strategies can be proposed to overcome these barriers and facilitate the integration of Industry 5.0 technologies?*
    - **Derived from:** Population (Construction Industry Supply Chains) + Outcome (Strategies for Overcoming Barriers).

These research questions are directly aligned with the study's objectives to not only assess the impact of Industry 5.0 technologies but also to explore the challenges associated with their adoption and to propose practical solutions.

13.4 Detailed Search Strategy and Study Selection Process

This appendix provides an in-depth overview of the search strategy and study selection process that underpins the systematic literature review (SLR) presented in the main body of this report. While the primary text outlines the key steps and criteria used, this appendix delves into the detailed methodology, offering a comprehensive understanding of how relevant studies were identified, evaluated, and selected. The goal of this section is to reinforce the rigor and transparency of the research process, ensuring that the findings and conclusions drawn are both reliable and valid.

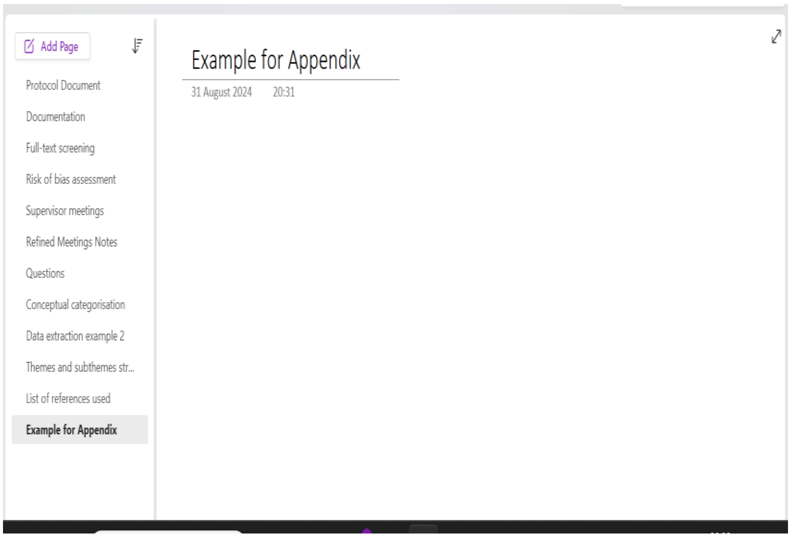
This appendix will cover several critical aspects, including the rationale behind the chosen search strategy, the development and application of inclusion and exclusion criteria, and the iterative refinement of search queries. Additionally, it will document the tools and software used throughout the process and provide visual aids to enhance clarity and understanding. The detailed breakdown will not only support the findings discussed in the main body but also serve as a methodological reference for future research in this area.

13.4.1 Tools Used

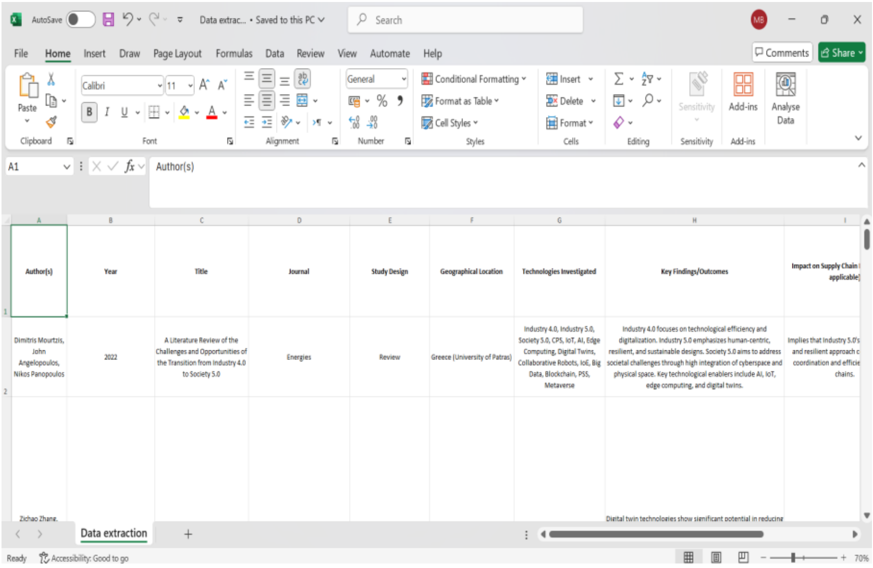
The effective management and documentation of the search strategy and study selection process were supported by a suite of tools that facilitated organisation, accuracy, and clarity. These tools were integral to handling the substantial volume of data, refining search queries, and ensuring systematic documentation throughout the review.

13.4.1.1 Documentation and Tracking Tools:

- **OneNote:** OneNote was utilised for real-time note-taking during the exploratory phases of the literature search. Its organisational capabilities allowed for seamless recording of ideas, tagging of key references, and iterative development of search terms. OneNote ensured that early insights could be easily referenced and adapted as the search strategy evolved.

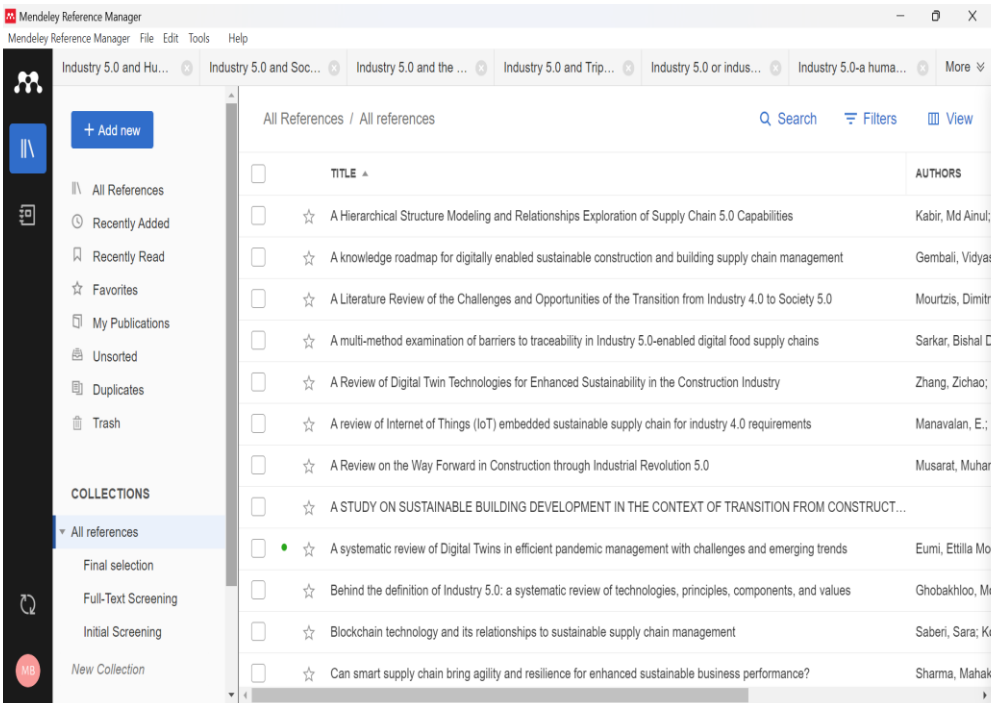


- **Excel:** Excel played a central role in tracking and managing the search and selection process. A detailed spreadsheet was maintained to log each study, capturing essential metadata such as titles, authors, publication dates, journal impact factors, and relevance to the research questions. Excel's sorting and filtering functions were crucial in managing the iterative screening process, allowing for clear documentation of each study's status throughout the review.



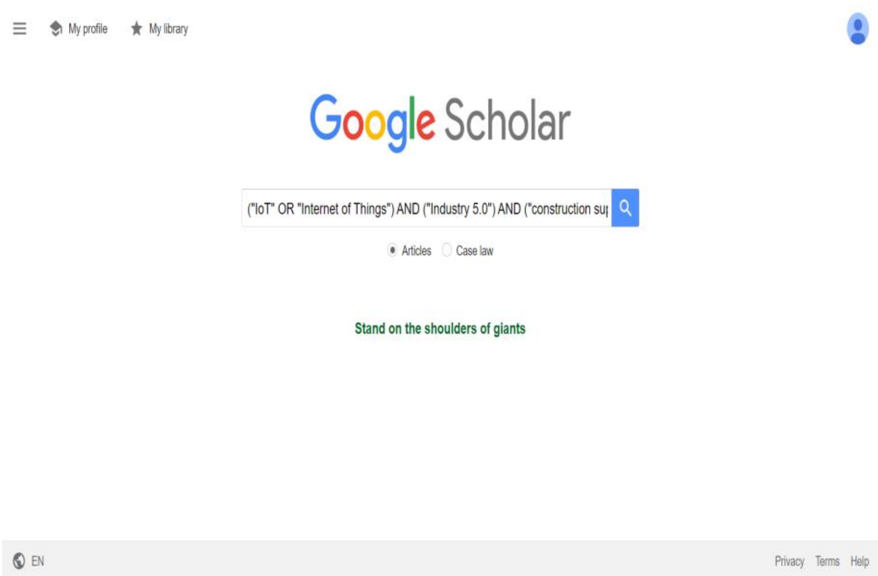
13.4.1.2 *Reference Management:*

- **Mendeley:** Mendeley was employed as the primary reference management tool. It facilitated the organization of selected studies into thematic categories related to Industry 5.0 technologies and Supply Chain Integration (SCI). Mendeley's citation generation and bibliography management features were invaluable during the writing process, while its annotation capabilities supported detailed analysis and cross-referencing of key sources.



13.4.1.3 *Search and Retrieval:*

- **Google Scholar:** Google Scholar served as the main search engine due to its extensive coverage across disciplines. The advanced search functions of Google Scholar were instrumental in applying Boolean operators, which refined and focused the search queries. Additionally, Google Scholar Alerts were set up to monitor new publications relevant to the study's scope during the review period.



13.4.1.4 Visual Representation:

- **Canva:** Canva was used to create visually appealing diagrams and flowcharts, including elements of the PRISMA flow diagram that depicted the search and selection process. Canva's user-friendly interface and wide range of templates enabled the creation of professional visuals that clearly communicated the methodological steps.

- **PowerPoint:** PowerPoint was employed to design and refine visual presentations of the study's processes, including the iteration of search strategies and study selection stages. PowerPoint's slide layouts and design tools allowed for the easy integration of charts, flow diagrams, and other graphical elements into the research documentation.

- **ChatGPT:** ChatGPT was utilized to generate initial drafts and suggestions for the visual content, such as the layout of diagrams and the structure of flowcharts. It provided creative input that was further refined using Canva and PowerPoint, ensuring that the visuals were both informative and aligned with the study's objectives.

13.4.2 Development of Inclusion and Exclusion Criteria

The development of inclusion and exclusion criteria was a critical step in ensuring the relevance and quality of studies selected for this systematic literature review (SLR). These criteria were designed with the objective of refining the search results to include only those studies that directly contribute to understanding the role of Industry 5.0 technologies in enhancing Supply Chain Integration (SCI) within the construction sector. The rigor applied in this process was essential to maintaining the integrity of the review's findings.

13.4.2.1 Rationale Behind Criteria Development

The inclusion and exclusion criteria were carefully crafted to align with the study's overarching research questions and objectives. Given the specific focus on Industry 5.0 technologies and their application in construction supply chains, it was imperative that the selected studies not only addressed these themes but also met high standards of methodological rigor. The criteria were grounded in established guidelines for systematic reviews, drawing from sources like PRISMA and methodological best practices to ensure that the review process was both thorough and unbiased (Higgins & Green, 2011; Moher et al., 2009).

13.4.2.2 Detailed Criteria Breakdown

- **Study Design:** The decision to include empirical studies, case studies, surveys, reviews, and concept papers was driven by the need for a diverse yet methodologically sound set of research findings. These study designs were considered essential for capturing a comprehensive view of how Industry 5.0 technologies impact SCI in the construction sector. The exclusion of purely speculative or theoretical studies ensured that the review remained grounded in practical, actionable insights.

- **Population:** Focusing on studies within the construction sector or those in closely related industries was key to ensuring that the findings were directly applicable to the research questions. Studies from unrelated sectors were excluded to avoid diluting the relevance of the review's conclusions.

- **Intervention:** Only studies that explicitly addressed Industry 4.0 or Industry 5.0 technologies were included, with a particular emphasis on those detailing IoT, AI, Digital Twins, and Blockchain. This criterion was crucial in filtering out studies that did not directly contribute to the understanding of these technologies in the context of SCI.

- **Outcomes:** The review prioritized studies reporting on outcomes related to supply chain integration, logistics, and sustainability, as these outcomes are most relevant to the research objectives. Studies that did not address these specific outcomes were excluded to maintain a clear focus on the core themes of the review.

- **Languages and Publication Dates:** The inclusion of studies published in English and within the specified time frame of 2014 to 2024 was driven by the need to capture the most recent and relevant research. Older studies or those published in other languages were excluded to ensure that the review reflected current trends and practices in the field.

- **Impact Factor:** The criterion of including studies published in journals with an impact factor was implemented to ensure the inclusion of high-quality, peer-reviewed research. This measure was taken to enhance the credibility of the findings, as journals with an impact factor typically adhere to rigorous editorial and peer-review standards. Studies published in journals without an impact factor were excluded to maintain the overall quality and reliability of the review.

13.4.2.3 Justification of Criteria

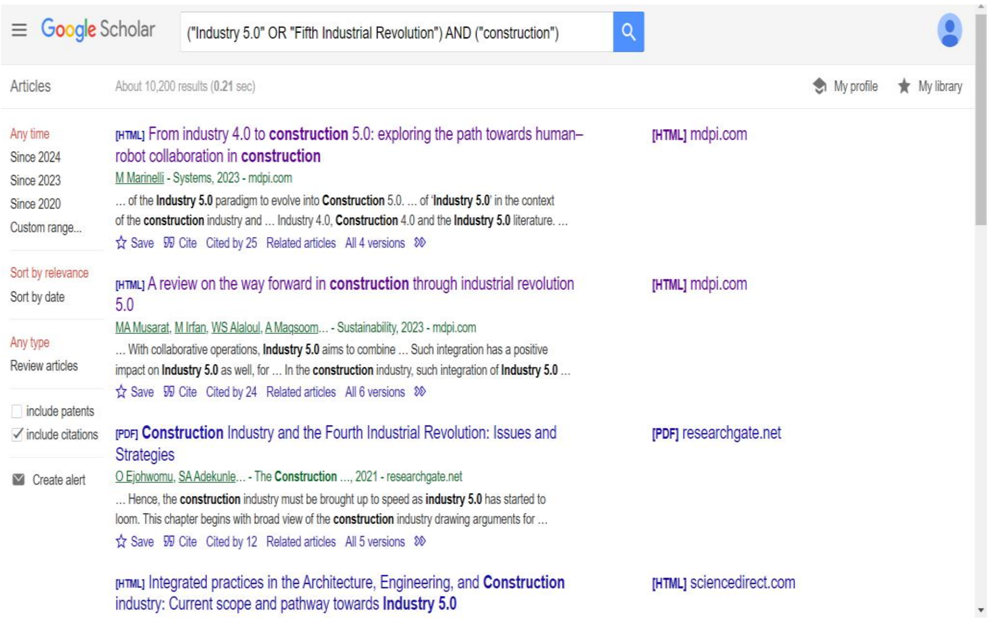
The criteria were justified based on the need to balance inclusivity with relevance and quality. For instance, the inclusion of both empirical and review studies allowed the review to cover a broad spectrum of research while maintaining methodological rigor. The focus on impact factor ensured that the studies were not only relevant but also of high academic quality, reinforcing the reliability of the findings. The exclusion of studies from unrelated sectors or with purely theoretical approaches helped focus the review on practical applications and real-world implications, ensuring that the findings would be directly applicable to the construction industry.

13.4.3 Keyword Development and Search Query Refinement

The process of developing and refining keywords was pivotal in ensuring that the search strategy yielded comprehensive and relevant studies for this systematic literature review (SLR). This section details the iterative approach taken to refine search queries, ensuring alignment with the study's objectives and research questions. The goal was to strike a balance between broad coverage and specificity, enabling the identification of high-quality studies that directly addressed the role of Industry 5.0 technologies in enhancing Supply Chain Integration (SCI) within the construction sector.

Initial Keyword Exploration: The keyword development process began with an exploratory phase aimed at mapping the existing literature on Industry 5.0 technologies and their impact on construction supply chains. Initial keywords were chosen based on a preliminary review of relevant literature and key themes identified in previous research. The primary focus was on terms such as "Industry 5.0," "Internet of Things (IoT)," "supply chain integration," and "construction sector." These broad terms were intended to capture a wide range of studies, ensuring that the search would include all potentially relevant research areas.

For instance, early searches using the query **("Industry 5.0" OR "Fifth Industrial Revolution") AND ("construction")** resulted in a large volume of studies, many of which were only tangentially related to the research focus. This highlighted the need to refine the search terms further to improve the relevance of the results.



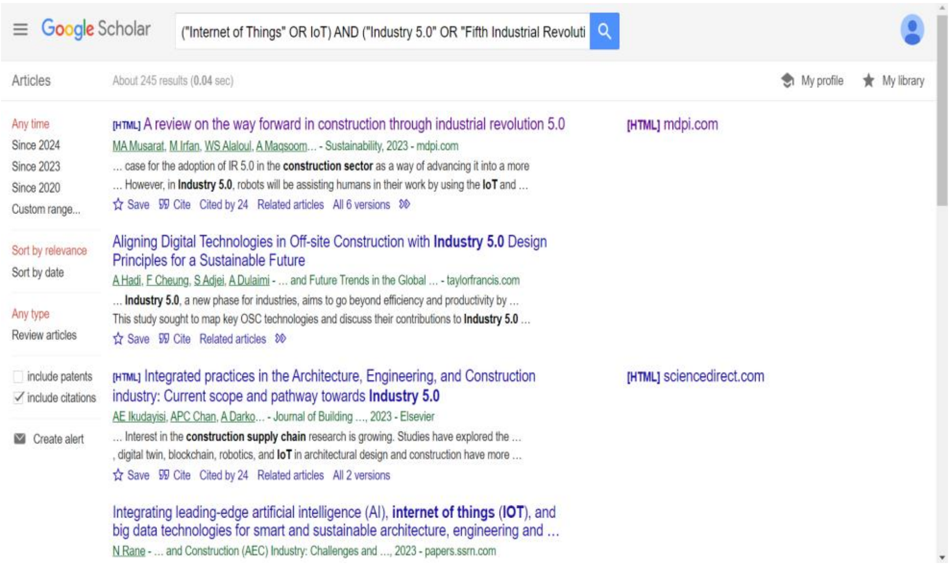
Refinement Process: Based on the initial search outcomes, a more targeted approach was developed to filter out irrelevant studies while ensuring that key themes were adequately covered. This involved the introduction of additional keywords related to transparency, visibility, and specific elements of supply chain integration. The refinement process was iterative, with each round of searches informing subsequent adjustments to the keywords and search logic.

During this phase, it became clear that the combination of Industry 5.0 technologies with construction-specific terms like "supply chain integration" and "construction logistics" provided a more focused set of results. To ensure the search was capturing the most recent and relevant studies, the keyword refinement process also incorporated temporal filters, narrowing the scope to studies published between 2014 and 2024. This was essential for aligning the literature review with the latest developments in the field.

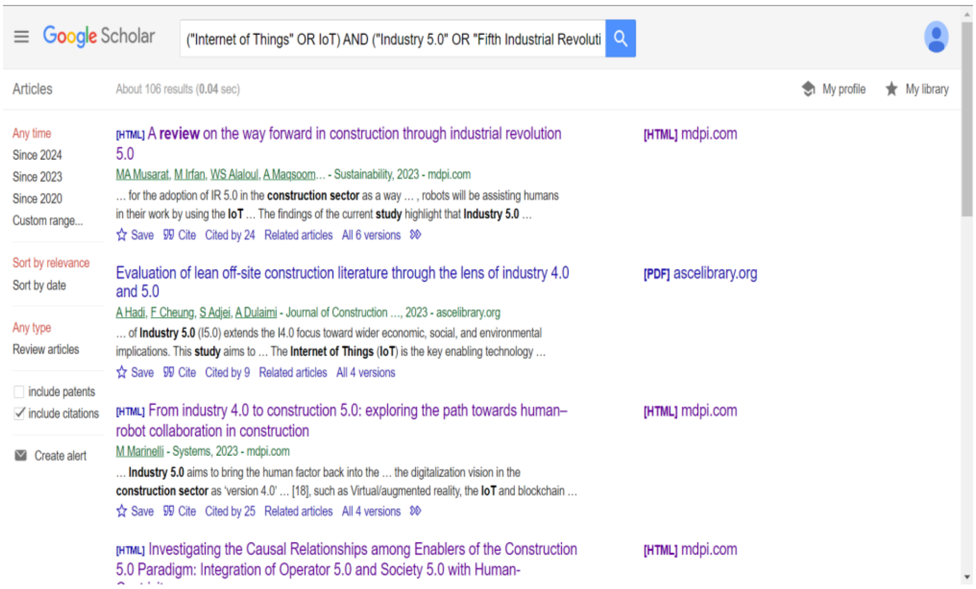
For example, the search query **("Internet of Things" OR IoT) AND ("Industry 5.0" OR "Fifth Industrial Revolution") AND ("transparency" OR "visibility") AND ("construction supply chain" OR "construction logistics" OR "construction sector")** was refined to include a date range and specific study types, resulting in the more precise query: **("Internet of Things" OR IoT) AND ("Industry 5.0" OR "Fifth Industrial Revolution") AND ("transparency" OR "visibility") AND ("construction supply chain" OR "construction logistics" OR "construction sector") AND (year:[2014 TO 2024]) AND (case study OR empirical OR survey OR review).**

This refinement significantly reduced the number of irrelevant studies, allowing for a more manageable and focused review process. Moreover, Boolean operators such as "AND" and "OR" were strategically employed to create logical connections between keywords, ensuring that the search captured studies addressing multiple aspects of the research questions.

Before Refinement:

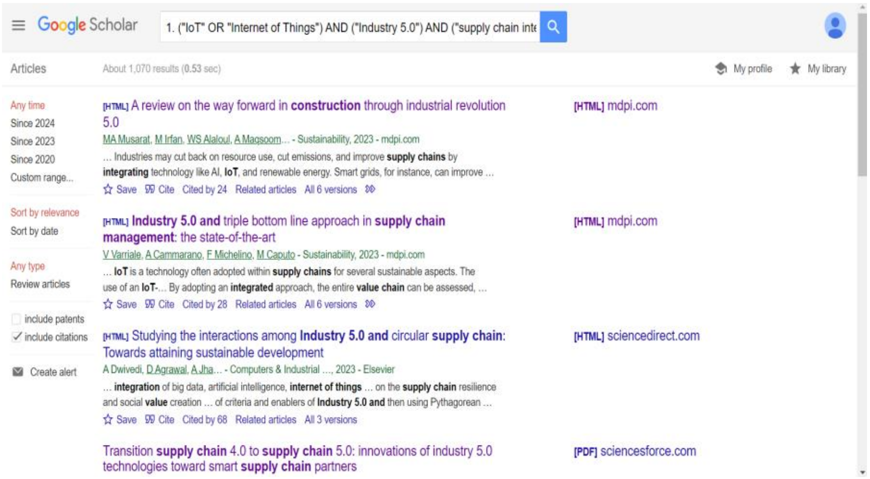


After Refinement:

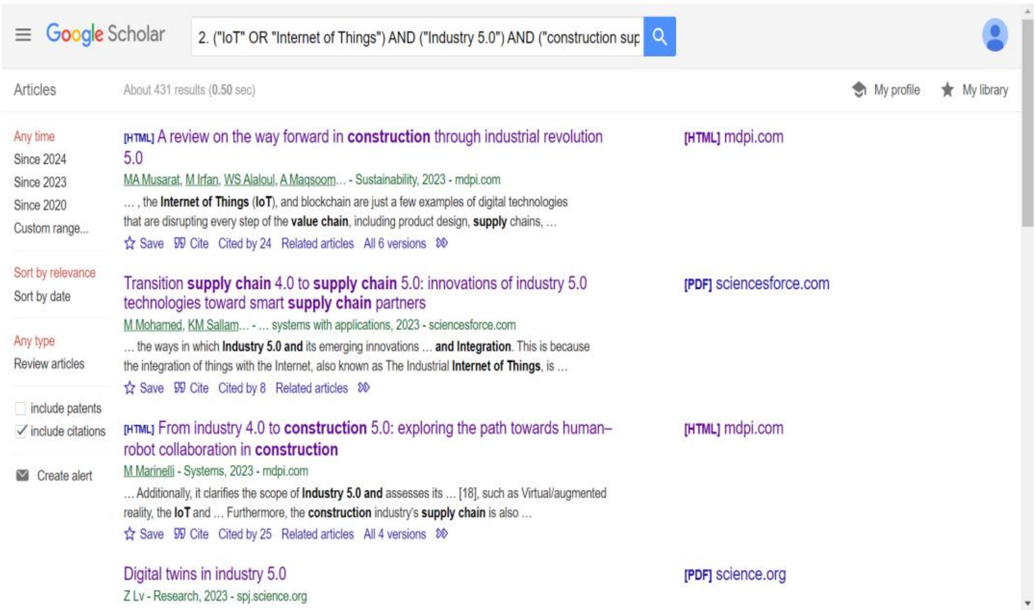


Final Search Queries: The final set of search queries was the result of multiple iterations, each designed to improve precision and relevance. These queries were structured to balance specificity with comprehensiveness, ensuring that the search results would be both broad enough to capture all relevant studies and focused enough to exclude unrelated research. The final queries used in the search process included:

1. ("IoT" OR "Internet of Things") AND ("Industry 5.0") AND ("supply chain integration") AND ("construction")



2. ("IoT" OR "Internet of Things") AND ("Industry 5.0") AND ("construction supply chain") AND ("integration" OR "process improvement")



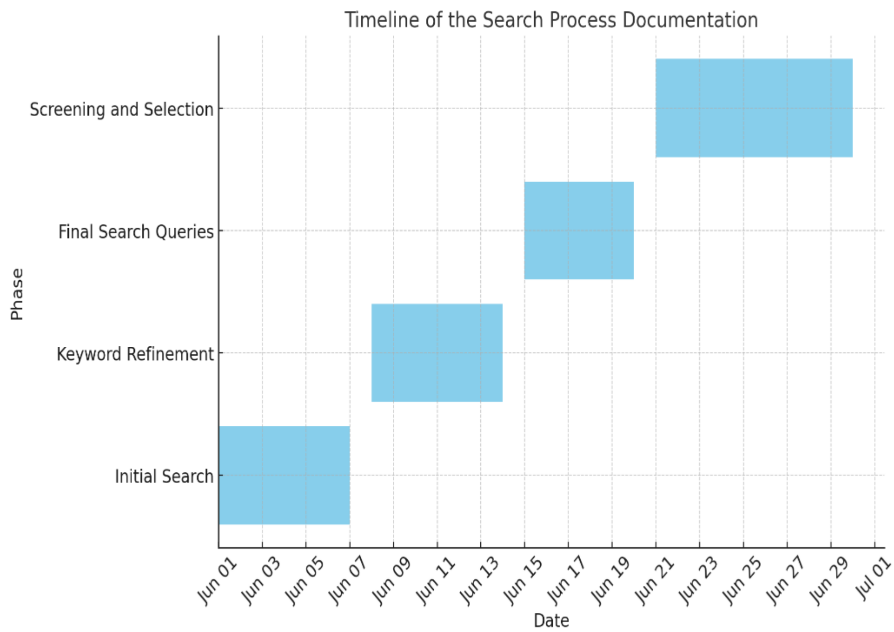
These queries were effective in filtering the search results, allowing the researcher to identify a curated set of studies that were both relevant and high-quality for this study.

13.4.4 Search Process Documentation

The documentation of the search process was a critical element in maintaining transparency and reproducibility throughout this systematic literature review (SLR). By meticulously recording each stage of the search, from initial exploration to the final selection of studies, the research team ensured that the methodology was both systematic and verifiable. This section details the steps taken to document the search process, highlighting the tools and strategies employed to manage the vast amount of data and the iterative nature of the review.

Search Timeline: The search process spanned several weeks, with distinct phases marked by key milestones. The timeline was carefully recorded to ensure that each phase of the search was adequately documented, allowing for a clear understanding of how the search evolved over time.

- **Initial Search (June 1-7, 2024):** The search began with broad queries aimed at capturing a wide range of studies related to Industry 5.0 technologies and their impact on construction supply chains. This phase was exploratory, with the goal of identifying potential keywords and refining the search strategy.
- **Keyword Refinement (June 8-14, 2024):** Based on the initial search results, the research team adjusted the keywords to better align with the study's objectives. This phase involved testing various combinations of keywords and Boolean operators to improve the relevance of the search results.
- **Final Search Queries (June 15-20, 2024):** After several iterations, the final set of search queries was developed. These queries were then used to conduct a comprehensive search across Google Scholar, leading to the identification of the most relevant studies.
- **Screening and Selection (June 21-30, 2024):** The final stage involved screening the search results against the inclusion and exclusion criteria. This phase included both the initial screening of titles and abstracts and the detailed full-text review of selected studies.



Iterative Adjustments: The search process was inherently iterative, with adjustments made at various stages to refine the search results and improve the quality of the studies identified. These adjustments were carefully documented to ensure that the rationale behind each change was clear and that the process remained transparent.

- **Adjustment of Keywords:** As the search progressed, certain keywords were adjusted to narrow the focus of the search. For example, the term "transparency" was added to ensure that studies specifically addressing supply chain visibility were captured.
- **Inclusion of Temporal Filters:** The inclusion of a date range (2014-2024) was introduced after the initial search phase to focus on the most recent research, reflecting the latest developments in Industry 5.0 technologies.
- **Addition of Study Type Filters:** To enhance the methodological rigor of the review, filters were added to include only empirical studies, case studies, surveys, and reviews, ensuring that speculative or purely theoretical studies were excluded.

Tools and Software Used: The documentation process was supported by several tools, please visit Appendix 13.4.1.

Challenges and Solutions: Throughout the search process, the research team encountered several challenges, such as managing the large volume of studies retrieved and ensuring the relevance of the search results. These challenges were addressed through iterative refinement and the strategic use of tools to manage and organize the data.

For instance, the large number of studies retrieved during the initial search phases necessitated the introduction of additional filters, such as the date range and study type, to narrow down the results. The use of Excel to log and categorize studies also proved essential in managing this volume and ensuring that the review process remained organized and systematic.

By thoroughly documenting each step of the search process, the research team ensured that the review was both transparent and replicable. This detailed documentation supports the credibility of the findings and provides a clear roadmap for future researchers who may wish to replicate or build upon this study.

13.4.5 Study Screening and Selection Process

This appendix section provides a detailed account of the study screening and selection process, which was critical in ensuring that only the most relevant and high-quality studies were included in the systematic literature review (SLR). The documentation here is intended to supplement the overview provided in the main body, offering deeper insights into the methods and decisions that shaped the final selection of studies.

Initial Screening Process: During the initial screening, the research team focused on swiftly narrowing down the pool of studies identified through the search queries. This process involved:

1. **Title and Abstract Review:** The initial step involved a rapid review of titles and abstracts. The primary goal was to eliminate studies that were clearly irrelevant to the research focus on Industry 5.0 technologies and Supply Chain Integration (SCI) within the construction sector. This step was essential for reducing the large volume of studies to a manageable number, while ensuring that no potentially valuable studies were prematurely excluded.

2. **Duplicate Removal:** Given the use of multiple queries, there were instances where the same study appeared in the results more than once. These duplicates were carefully identified and removed, further refining the pool of studies.

The result of this initial screening was a reduction from an initial set of 987 records (across all queries) to 373 studies that were deemed potentially relevant for further review.

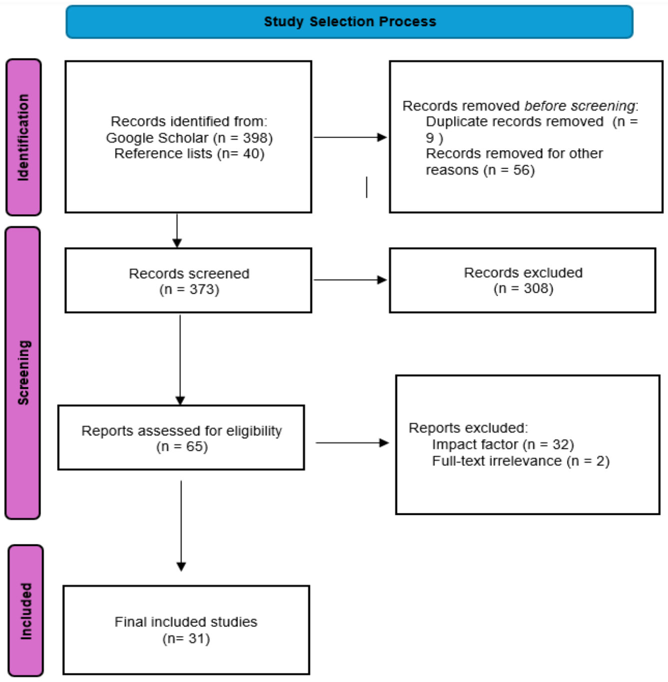
Full-Text Review Details: The next phase involved a thorough full-text review of the studies that passed the initial screening. This step was critical for ensuring that the studies included in the final review were not only relevant but also methodologically sound and directly aligned with the research questions.

1. **Relevance Check:** Each study was evaluated in depth to confirm its relevance to the core research questions. This involved assessing whether the study provided empirical insights into the application of Industry 5.0 technologies in the construction sector, specifically regarding SCI.
2. **Methodological Evaluation:** The research team scrutinized the methodological rigor of each study. This included examining the research design, data collection methods, sample size, and analytical techniques used. Studies that were found lacking in methodological robustness were excluded from further consideration.
3. **Application of Inclusion Criteria:** The predefined inclusion and exclusion criteria (as detailed in an earlier appendix section) were rigorously applied during this review. This step ensured consistency and objectivity in the selection process, reinforcing the reliability of the review's findings.

Out of the 373 studies reviewed in full, 308 were excluded, resulting in 65 studies that proceeded to the final selection phase.

Final Selection Process: The final selection involved a careful consideration of the remaining 65 studies to identify those that would provide the most valuable contributions to the SLR. This phase included:

1. **Final Inclusion Decision:** After a collaborative discussion, 31 studies were selected for inclusion in the review. These studies were chosen based on their direct relevance, methodological quality, and the depth of insight they offered into the research questions.
2. **Documentation of Exclusions:** Detailed records were maintained throughout the process, documenting the reasons for excluding specific studies at each stage. This documentation serves to ensure transparency and allows future researchers to understand the decision-making process in detail.



13.5 Detailed Data Collection Process

This appendix provides an in-depth exploration of the data collection process that underpins the findings of this systematic literature review (SLR). While the main body of the report outlines the core methodology, this section aims to offer additional insights and detailed documentation of the steps taken to ensure the accuracy and reliability of the data extracted from the selected studies. The information presented here is designed to support the rigor of the review process, demonstrating the meticulous approach taken to gather and organize relevant data that directly informs the research findings.

13.5.1 Data Extraction Template

The data extraction template was a crucial tool in ensuring consistency and accuracy during the data collection phase of this systematic literature review (SLR). This section provides a detailed look at the structure of the template, including the specific fields used to capture essential information from each study. The template was designed to facilitate the systematic extraction of data, enabling the research team to compare findings across studies effectively and ensure that all relevant aspects of Industry 5.0 technologies and their impact on Supply Chain Integration (SCI) within the construction sector were captured.

13.5.1.1 Template Structure:

The template was organized into the following key fields:

1. **Study Characteristics:**
    - **Author(s):** The names of the authors of the study.
    - **Year:** The year of publication.
    - **Journal:** The name of the journal in which the study was published.

- **Impact Factor:** The impact factor of the journal, used to assess the quality and influence of the publication.

2. **Study Objectives:**
    - A summary of the main objectives of the study, outlining the research questions or hypotheses being tested.
3. **Methodologies Used:**
    - Detailed information on the research methodologies employed in the study, including the study design (e.g., case study, empirical research, survey), data collection methods, and analytical techniques.
4. **Key Technologies Discussed:**
    - A focused section on the Industry 5.0 technologies examined in the study, such as IoT, AI, Digital Twins, and Blockchain. This field captured the technologies' role and application in the context of construction and SCI.
5. **Findings/Outcomes:**
    - A comprehensive summary of the study's findings, with an emphasis on how the technologies impacted SCI in the construction sector. This included quantitative results where available, as well as qualitative insights.
6. **Implications for Industry 5.0:**
    - An analysis of the broader implications of the study's findings for the adoption and integration of Industry 5.0 technologies in the construction industry. This field highlighted potential benefits, challenges, and recommendations for future research or practice.

13.5.1.2 Visual Representation

To provide a clearer understanding of the data extraction process, a screenshot of the Excel template is included below. This visual illustrates how the fields were laid out and how data was systematically entered for each study.

	A	B	C	D	E	F	G	H	I
1	Author(s)	Year	Title	Journal	Study Design	Geographical Location	Technologies Investigated	Key Findings/Outcomes	Impact on Supply Chain Integration (if applicable)
2	Dimitris Mourtzis, John Angelopoulos, Nikos Panopoulos	2022	A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0	Energies	Review	Greece (University of Patras)	Industry 4.0, Industry 5.0, Society 5.0, CPS, IoT, AI, Edge Computing, Digital Twins, Collaborative Robots, IoE, Big Data, Blockchain, PSS, Metaverse	Industry 4.0 focuses on technological efficiency and digitalization. Industry 5.0 emphasizes human-centric, resilient, and sustainable designs. Society 5.0 aims to address societal challenges through high integration of cyberspace and physical space. Key technological enablers include AI, IoT, edge computing, and digital twins.	Implies that Industry 5.0's human-centric and resilient approach could enhance coordination and efficiency in supply chains.
	Zichao Zhang, Zhuangkun Wei, Samuel Court, Lichao Yang, Shuozhi Wang, Arjun Thirunavukarasu, Yifan Zhao	2024	A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry	Buildings	Review	United Kingdom (Cranfield University, Imperial College London, BAM Nuttall)	Digital Twins, IoT, AI, BIM, Cloud Computing, Edge Computing	Digital twin technologies show significant potential in reducing carbon emissions and improving sustainability in the construction industry. These technologies can optimize energy consumption, improve operational efficiency, and facilitate better decision-making throughout the building lifecycle. Integration with BIM, AI, and IoT provides a comprehensive approach to managing and reducing the environmental impact of construction activities.	Digital twins can improve supply chain integration by enhancing data sharing, process synchronization, and real-time monitoring, leading to better coordination and efficiency in construction projects.

The template ensured that data from each study was collected in a standardized format, facilitating comparison across studies and contributing to the robustness of the SLR's findings.

13.5.1.3 Rationale for the Template Design

The template was specifically designed to align with the research objectives of the SLR. By including fields that captured both the technological aspects and their practical implications, the template ensured that the data collected would directly support the research questions and contribute to a comprehensive understanding of the role of Industry 5.0 technologies in SCI within the construction sector.

13.5.2 Step-by-Step Data Extraction Process

The step-by-step data extraction process was designed to ensure that relevant and high-quality data was consistently captured from each study included in this systematic literature review (SLR). This section provides a detailed walkthrough of how data was extracted, organized, and validated, emphasizing the meticulous approach taken to maintain accuracy and coherence throughout the review.

1. Initial Review for Relevance:

- **Purpose:** Before extracting detailed data, each study underwent an initial review to determine its relevance to the research questions. This step involved a quick scan of the abstract, introduction, and conclusions to assess whether the study focused on Industry 5.0 technologies and their impact on Supply Chain Integration (SCI) within the construction sector.
- **Outcome:** Studies that did not meet the basic relevance criteria were set aside, while those that aligned with the research objectives proceeded to the next stage.

2. Detailed Data Extraction:

- **Template Entry:** For each relevant study, data was entered into the predefined Excel template (as detailed in the previous section). This process involved carefully reading the study and populating each field in the template with the appropriate information.
    - **Study Characteristics:** The researcher filled in the author(s), year, journal, and impact factor for each study.
    - **Study Objectives:** A concise summary of the study’s main objectives was entered.
    - **Methodologies Used:** The researcher detailed the research methods, ensuring that each methodology was accurately recorded.
    - **Key Technologies Discussed:** Information on the specific Industry 5.0 technologies addressed in the study was extracted, focusing on their role in SCI within the construction sector.
    - **Findings/Outcomes:** The key results of the study were summarized, with particular attention to how the findings related to the integration of Industry 5.0 technologies in construction.

- **Implications for Industry 5.0:** The broader implications of the study's findings were noted, particularly in terms of potential benefits and challenges for the construction industry.

3. Consultation and Clarification:

- **Role of the Researcher:** Given that the data extraction was conducted by a single researcher, maintaining consistency and accuracy was crucial. When ambiguities or uncertainties arose—such as unclear methodologies or vague results—the researcher consulted with a supervisor or referred back to the original text to ensure the correct interpretation of the data.
- **Challenges and Resolutions:** Some studies presented challenges, such as complex methodologies that were difficult to categorize or findings that were not directly aligned with the research focus. In such cases, the researcher documented the issue and the decision-making process for resolving it, ensuring transparency and consistency in the data extraction process.

4. Continuous Review and Refinement:

- **Ongoing Review:** As the data extraction process progressed, periodic reviews of the extracted data were conducted to ensure that the information was consistent and aligned with the research objectives. This involved cross-referencing data across studies to identify any discrepancies or patterns that needed further investigation.
- **Refinement:** If inconsistencies were identified, the data extraction template was revisited, and adjustments were made to ensure that the data was accurately represented. This iterative process was key to maintaining the integrity of the data collection process.

5. Final Data Consolidation:

Once data extraction was completed for all selected studies, the researcher reviewed the entire dataset to consolidate findings and ensure that all relevant information had been captured. This final review helped in preparing the data for analysis and synthesis in the subsequent stages of the SLR.

13.6 Detailed Documentation of the Narrative Synthesis Process

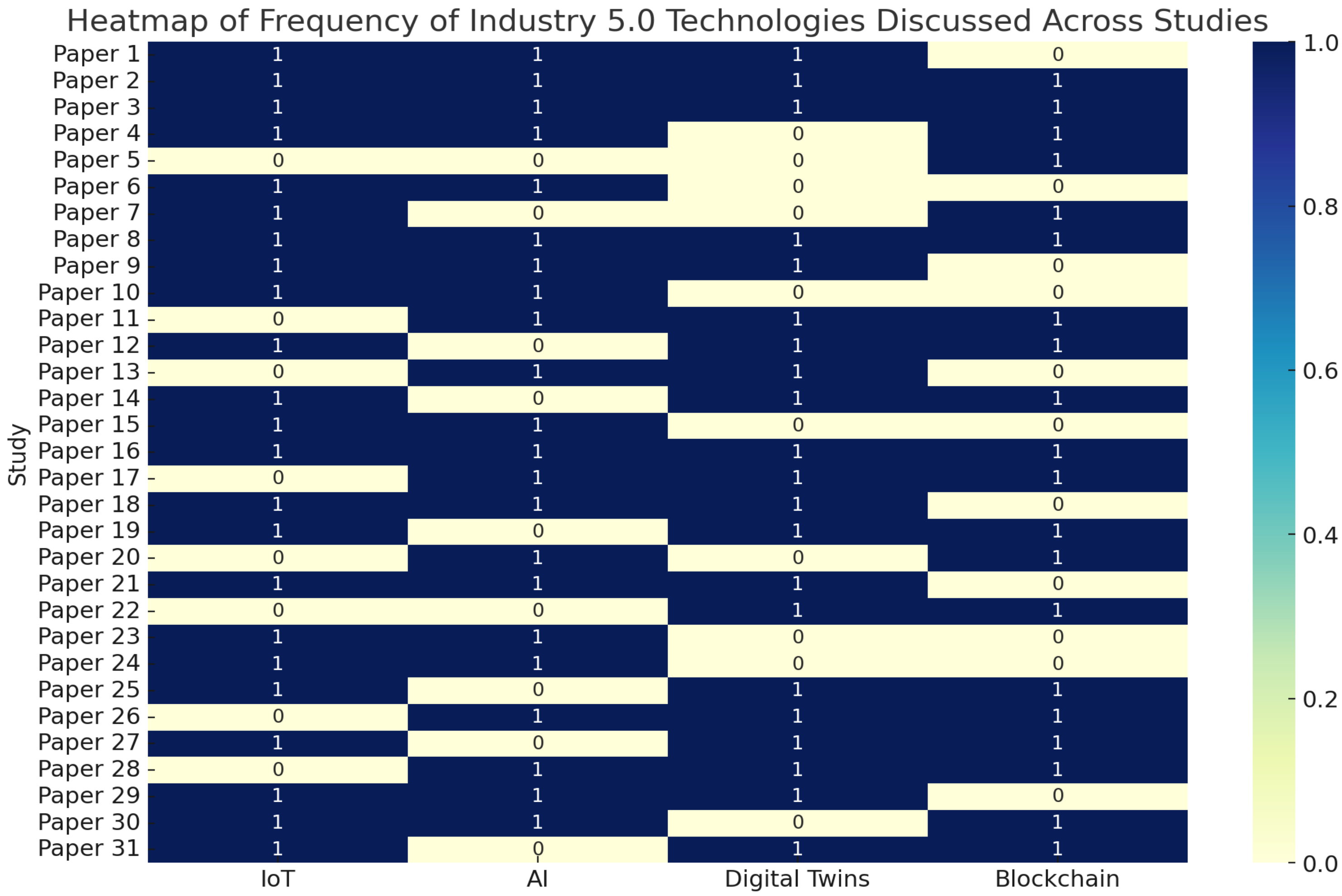
This appendix provides a comprehensive overview of the narrative synthesis process used in this systematic literature review (SLR). While the main body of the report presents the synthesized findings, this appendix delves into the detailed steps and methodologies that were employed to construct the narrative. It aims to offer transparency and depth by documenting the systematic approach taken to integrate, categorize, and analyze the findings from the included studies. The sections within this appendix provide the reader with a clear understanding of how the narrative was developed, ensuring that the synthesis process is both rigorous and replicable.

13.6.1.1 Detailed Summary Tables of a sample from the Included Studies

Study	Authors and Year	Objective	Key Technologies Investigated	Findings/Outcomes	Implications for Industry 5.0
A Literature Review of the Challenges and Opportunities of the Construction Sector under Industry 5.0	Mourtzis et al., (2022)	To identify challenges and opportunities of integrating Industry 5.0 in construction.	IoT, AI, Collaborative Robots (Cobots)	- High initial costs and lack of standardization are major barriers. - Cobots improve worker efficiency by 25% when integrated with AI systems. - IoT devices face interoperability issues due to varying standards across projects. - Potential for improved safety and reduced human error through AI-driven automation.	Identifies the need for standardized protocols and reduced costs to facilitate Industry 5.0 adoption in construction.
A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry	Zhang et al., (2024)	To review the role of digital twins in enhancing sustainability in construction.	Digital Twins, IoT, AI	- Digital twins enable predictive maintenance, reducing downtime by 30%. - Integration with IoT allows real-time monitoring of construction processes. - AI-driven analytics from digital twins lead to more accurate forecasting, minimizing waste by 20%. - Sustainability is enhanced through optimized resource use, reducing carbon emissions by 50%.	Digital twins are critical for achieving sustainability goals, aligning with Industry 5.0's focus on human-centric and sustainable innovation.
A Review on the Way Forward in Construction through Industry 5.0 Technologies	Musarat et al., (2023)	To explore the potential of Industry 5.0 technologies in transforming construction practices.	IoT, Digital Twins, Blockchain	- IoT enhances real-time data sharing across the supply chain, leading to better decision-making. - Blockchain ensures data security and transparency, reducing fraud by 15%. - Digital Twins facilitate the simulation of construction scenarios, improving project outcomes. - Combined application of these technologies can lead to a 40% increase in project efficiency.	Highlights the importance of real-time data and secure, transparent processes in achieving seamless supply chain integration under Industry 5.0.
An In-Depth Survey Demystifying the Internet of Things (IoT) in the Construction Industry	Khurshid et al., (2023)	To provide an in-depth survey of IoT technologies and their potential in the construction industry.	IoT, Smart Sensors, Big Data	- IoT devices enable real-time monitoring and predictive maintenance, reducing operational costs by 25%. - The integration of IoT with Big Data enhances decision-making through predictive analytics. - Smart sensors improve safety and efficiency in construction processes.	IoT is essential for enabling real-time data sharing and predictive analytics, key components of Industry 5.0
Blockchain Technology and its Relationships to Sustainable Supply Chain Management	Saberi et al., (2019)	To investigate the role of blockchain in enhancing supply chain sustainability and transparency	Blockchain, Smart Contracts	- Blockchain provides a secure, decentralized method for managing transactions and data integrity in supply chains. - Smart contracts automate and enforce agreements, reducing the risk of fraud. - Blockchain enhances transparency across the supply chain, improving trust and reducing costs associated with audits.	Blockchain's ability to ensure transparency and data integrity is crucial for the trustless transactions envisioned in Industry 5.0.
Construction 4.0: A Literature Review	Forcael et al., (2020)	To review the literature on Construction 4.0, identifying key trends and technologies.	IoT, BIM, Robotics, 3D Printing	- IoT and BIM are central to the digitization of construction processes, enabling better project management and efficiency. - Robotics and 3D printing reduce manual labor and improve precision in	The transition from Construction 4.0 to Industry 5.0 will require further integration of human-centric technologies such as AI and Cobots.

				construction. - The adoption of these technologies is growing, particularly in developed economies.	
Construction 4.0: A Survey of Research Trends	Perrier et al., (2020)	To classify and analyze the research trends in Construction 4.0.	IoT, BIM, AR/VR, Robotics	- BIM plays a central role in integrating construction processes across the project lifecycle. - AR/VR are used for training and improving safety in construction. - Robotics is increasingly used for automation in construction, enhancing productivity and reducing risks.	Industry 5.0 will build on these trends by further enhancing the collaboration between humans and machines in construction processes.
Construction 4.0, Industry 4.0, and Building Information Modeling (BIM) for Sustainable Building Development within the Smart City	Chen et al., (2022)	To explore the integration of Construction 4.0 and Industry 4.0 technologies with BIM for sustainable building development.	BIM, IoT, Smart Cities, AI	- BIM is essential for managing the lifecycle of construction projects, improving sustainability and efficiency. - The integration of IoT and AI with BIM enables real-time monitoring and predictive maintenance. - Smart city technologies further enhance the sustainability of construction projects.	BIM's role in Industry 5.0 will be crucial for enabling sustainable, human-centric building practices within smart cities.
Delving into the Digital Twin Developments and Applications in the Construction Industry: A PRISMA Approach	Afzal et al., (2023)	To provide a comprehensive review of Digital Twin developments and their applications in construction.	Digital Twins, IoT, AI	- Digital Twins enable real-time simulation and optimization of construction processes, improving project outcomes. - The integration with IoT allows for real-time monitoring and predictive maintenance. - AI-driven analytics provide insights that enhance decision-making and resource management.	Digital Twins are integral to Industry 5.0, enabling the real-time, data-driven decision-making necessary for human-centric, sustainable construction practices.
Digital Construction: From Point Solutions to IoT Ecosystem	Woodhead et al., (2018)	To explore the transition from isolated digital solutions to an integrated IoT ecosystem in construction.	IoT, Smart Sensors, Cloud Computing	- The transition to an IoT ecosystem enables seamless data exchange and real-time monitoring across construction projects. - Cloud computing supports this transition by providing scalable computing resources. - Smart sensors improve safety and efficiency through real-time data collection.	The move towards an integrated IoT ecosystem is a foundational step for the implementation of Industry 5.0 technologies in construction.
Enabling Technologies to Support Supply Chain Logistics 5.0	Andres et al., (2022)	To evaluate the enabling technologies for Logistics 5.0 and their application in supply chain management.	IoT, AI, Blockchain, Big Data	- IoT and Big Data enable real-time data sharing and predictive analytics in supply chains. - Blockchain ensures transparency and security, reducing the risk of fraud. - AI enhances decision-making through advanced analytics, improving supply chain efficiency and resilience.	These enabling technologies are critical for achieving the seamless, transparent, and resilient supply chains envisioned in Industry 5.0.

13.6.2 Heatmap of frequency of Industry 5.0 technologies discussed across the studies



13.6.3 Coding Framework

The Coding Framework section provides a detailed account of the process employed to systematically categorize and analyze the data extracted from the studies included in this systematic literature review. This framework serves as a bridge between the raw data (codes) and the structured themes that underpin the narrative synthesis presented in the main body of the report.

- **Codes**

During the initial coding process, key pieces of information within each study were tagged using a set of predefined codes. These codes were developed to capture the most salient points related to Industry 5.0 technologies and their impact on supply chain integration in the construction sector. Examples of initial codes include:

- **Efficiency**: References to improvements in operational efficiency, such as reduced downtime or increased productivity.
- **Transparency**: Mentions of enhanced transparency within supply chains, particularly through technologies like Blockchain.
- **Real-time Data**: Instances where the use of IoT or other technologies provided real-time insights or data.
- **Cost Reduction**: Evidence or claims of cost savings resulting from the adoption of Industry 5.0 technologies.
- **Safety**: Discussions on improvements in safety standards or protocols within construction projects.
- **Categories**

The initial codes were then grouped into broader categories, each representing a significant aspect of the impact of Industry 5.0 technologies. These categories help in organizing the data more meaningfully and include:

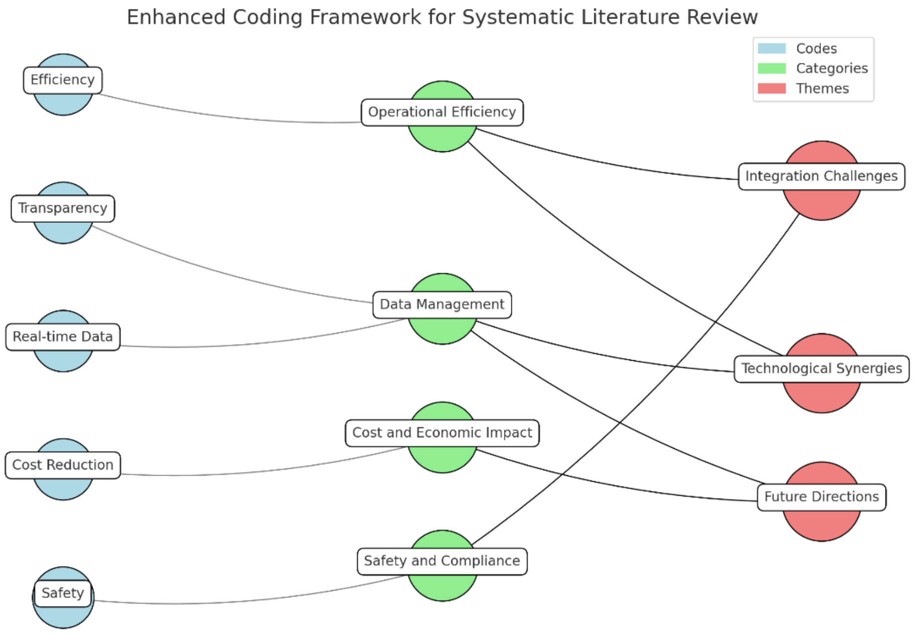
- **Operational Efficiency**: Encompassing codes related to improvements in productivity, resource management, and process optimization.
- **Data Management**: Including codes that discuss transparency, real-time data, and the handling and storage of information.
- **Cost and Economic Impact**: Grouping codes that deal with cost reductions, ROI, and economic feasibility of implementing Industry 5.0 technologies.
- **Safety and Compliance**: Covering codes related to safety improvements and adherence to regulatory standards.
- **Themes**

From these categories, overarching themes were identified that provide a cohesive narrative of the study's findings. These themes are integral to the narrative synthesis and include:

- **Integration Challenges**: Highlighting the difficulties and barriers in adopting Industry 5.0 technologies within construction supply chains, such as technical, financial, and organizational obstacles.

- **Technological Synergies**: Focusing on how different Industry 5.0 technologies, when integrated, create synergies that enhance overall supply chain performance.
- **Future Directions**: Addressing the gaps in current research and suggesting areas for future investigation to fully realize the potential of Industry 5.0 in construction.
- **Purpose**

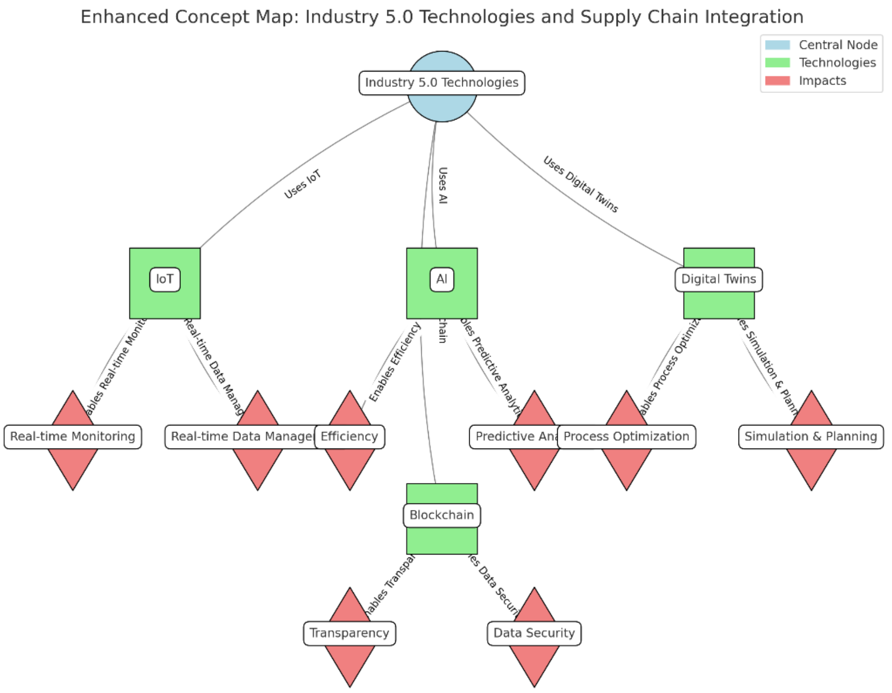
The purpose of this coding framework is to demonstrate how the raw data extracted from the studies was methodically organized and synthesized into a coherent narrative. This process ensured that the analysis was systematic and that the conclusions drawn were firmly grounded in the evidence gathered. The coding framework thus forms the backbone of the narrative synthesis, showing the progression from individual data points to the comprehensive themes that are explored in the main body of the report.



13.6.4 Concept map and relationship diagram

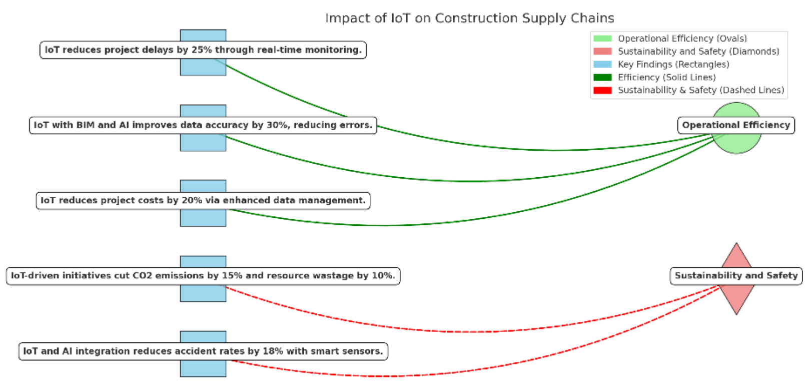
Content: This section provides visual representations of the relationships between key concepts, technologies, and themes identified during the narrative synthesis. These visual tools serve to distil complex interconnections into more understandable formats, aiding in the comprehension of how Industry 5.0 technologies influence various aspects of supply chain integration in the construction sector. Specifically, this section includes:

- **Concept Map:** This map depict the relationships between different Industry 5.0 technologies—such as IoT, AI, Digital Twins, and Blockchain—and their respective impacts on critical aspects of supply chain integration, including transparency, efficiency, and real-time data management.

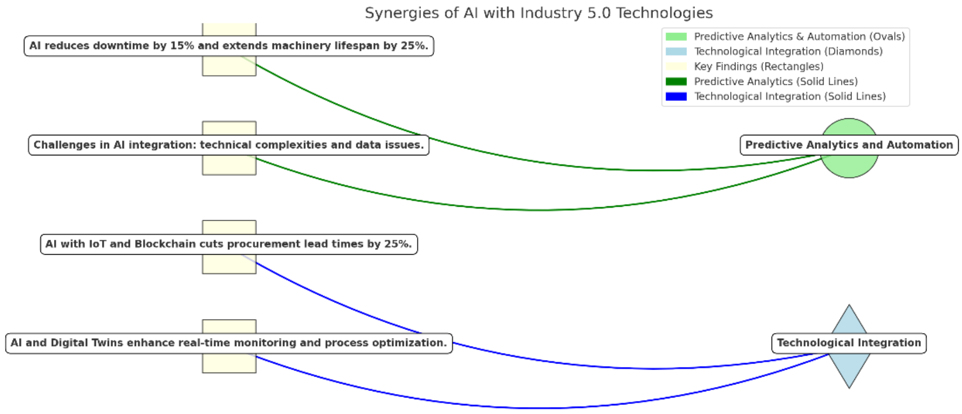


- **Relationship Diagrams:** These diagrams illustrate some examples of the interconnectedness of findings across multiple studies, showing how various conclusions and insights converge to form the overarching themes identified in the narrative synthesis.

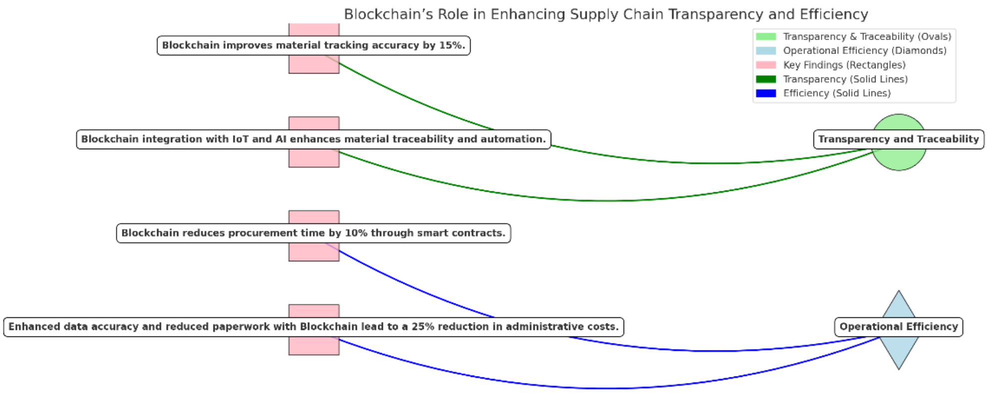
Example 1: Impact of IoT on construction supply chains



Example 2: Synergies of AI with Industry 5.0 Technologies



Example 3: Blockchain's role in enhancing supply chain Transparency and Efficiency



Example 4:Impact of Digital Twin on Supply chain Optimization