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A COMPREHENSIVE ANALYSIS OF THE IMPORTANCE OF INVESTIGATING THE IMPACT OF CONSTRUCTION 4.0 SKILLS ON PROJECT PERFORMANCE

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SUMMARY*: Construction projects often face challenges of poor performance, resulting in increased costs, delays, and defects. To address these issues, Construction 4.0 (C4.0) employs innovative technologies to enhance project efficiency, safety, and sustainability. However, construction projects lag in adopting these technologies, meeting significant obstacles, with the inadequately trained workforce being a major, underexplored difficulty leading to subpar construction project performance. This study aims to investigate the current status of existing research on C4.0 skills and construction project performance. To achieve this aim, this study conducts a systematic literature review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method on 50 articles. The findings suggest that general Construction 4.0 skills are recognized, but the specific impact on construction projects during the fourth industrial revolution stays unexplored. The study findings emphasize the need for targeted research to identify and examine Construction 4.0 skills crucial for construction projects.*

KEYWORDS*: Industry 4 0, Construction, Project Performance, Construction 4 0, Skill Development, Systematic Literature Review, Bibliometric Analysis, Scientometric Analysis.*

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1. INTRODUCTION

In recent years, the complexity of construction projects has multiplied, along with the budgetary and time constraints, as well as quality requirements (Shafei et al., 2022a). More essential is the contribution of construction projects to nations' gross domestic product (GDP). According to the World Economic Forum (Schwab & Zahidi 2020), construction projects generate approximately USD 10 trillion in annual revenues, USD 3.6 trillion in added values, and 6% of the global GDP. In addition, it accounts for approximately 5% and 8% of GDP in developed and developing nations. Therefore, construction projects are essential as they directly and indirectly impact national economies. However, for different reasons during the project life cycle, construction projects frequently result in disappointment in completing within budget, schedule, and quality (Albtoush et al., 2022).

The core principles of construction projects, involving the use of heavy machinery and physically demanding manual labour, are essential to the overall practice of construction project execution (You & Feng, 2020). In developing countries, these projects often rely on traditional old labour-intensive methods, leading to challenges such as excessive energy consumption, environmental pollution, safety concerns, and low productivity (Darko & Chan, 2018). Consequently, there is a need to enhance construction project performance and introduce a new paradigm to project execution (Keogh & Smallwood, 2021). Despite the stability of construction practices in recent decades, the industry is on the verge of transformation

The Fourth Industrial Revolution (IR4.0) may change the construction industry. With its ambitious objectives, IR4.0 is bolstering advancements in construction projects. Construction 4.0 (C4.0) embodies this integration of cutting-edge technologies into construction, paralleling IR4.0. By leveraging technologies from IR.40, C4.0 enhances construction project performance through automated workflows and the use of robots. This term was used when automated workflows were made possible where via C4.0 robots (Oesterreich 2016). Innovations such as additive manufacturing and prefabrication methods have been introduced, offering cost savings and increased efficiency (Dallasega et al., 2018; Shafei et al., 2022b). Emerging construction and prefabrication technologies, supported by stationary sensors and RFID, promise to reduce the cost of coordination and minimize waste (Moshood et al., 2020). Moreover, C4.0 is revolutionizing the design, construction, and management of projects. Smart technologies enable on-site resolution of customer and construction issues in 2D, 3D, 4D, 5D, 6D, and 7D designs (Lekan et al., 2022).

Despite progressive technological advances, construction project performance remains among the lowest across project types (Turner et al., 2021). The adoption of IR4.0 technologies in construction has heightened the demand for skills development (Adepoju et al., 2022). The increased use of machinery and automated equipment or robotics, coupled with the necessity for interdisciplinary skills, is transforming job profiles and necessitating upgrades (Adepoju et al., 2022; Ras et al., 2017). As these new skills are not yet prevalent in the current workforce, there is a risk that C4.0 may exacerbate skill shortages and disparities more quickly than they can be resolved. Skill deficits arise when the labour force cannot supply enough workers with the required skills, (Alaloul et al., 2018; Mc Guinness and Ortiz, 2016). To mitigate these risks, implementing effective skills development strategies is essential.

Understanding the integration of C4.0 technologies and skills in construction projects has garnered increased scholarly publications in recent years. A quick review of existing research reveals different perceptions regarding the effectiveness and application of C4.0 technologies. Notably, no consensus exists on a significant relationship between C4.0 technologies and project performance. Earlier research primarily introduced various tools and methods aimed at similar objectives yet lacks a unified perspective on their practical application. These inconsistencies stem from the limited synthesis and integration of the existing research. Additionally, construction industry practitioners, especially in developing countries, are reluctant to adopt C4.0 technologies due to a lack of awareness about their effectiveness and distinct advantages over conventional methods (Demirkesen & Tezel, 2021; Shafei et al., 2022b). Emphasizing the benefits and application strategies of C4.0 technologies can bridge this gap, fostering greater acceptance and enhancing project outcomes.

Given the extensive research done in this field, there is a need for a comprehensive overview to guide the direction of future research. Although research on C4.0 skills and construction project performance exists, a thorough synthesis of this body of knowledge is still lacking. By consolidating these diverse efforts, researchers can gain a better understanding of the relationship between C4.0 skills and construction project performance. This synthesis can also help identify knowledge gaps, paving the way for further research endeavours. Additionally, industry

practitioners can leverage the summarized information to select the most appropriate tools, techniques, and skills for their projects, thereby improving project outcomes.

The main aim of this study is to investigate the current state of existing research on C4.0 skills and construction project performance. The study aims to address the following research questions (RQs):

RQ1: What is the present status of existing research on C4.0 skills?

RQ2: What is the present status of existing research on C4.0 skills and project performance?

RQ3: What are the research gaps and future directions for C4.0 skills and project performance?

2. BACKGROUND

2.1 Construction 4.0

C4.0 signifies a fundamental change in construction projects by incorporating digital technologies to improve efficiency, performance, and sustainability. Organizations are progressively embracing C4.0 technologies, including robotics, 3D printing, artificial intelligence, and machine learning to optimize operations and enhance results. Existing research has thoroughly investigated the theoretical basis of C4.0, providing a clear understanding of its fundamental ideas and technological basis. For example, Maxwell presented a thorough summary of the fundamental ideas behind C4.0, highlighting the importance of digitalization, connectivity, and data analytics in revolutionizing conventional construction methods.

An example of a C4.0 application is Blechwarenfabrik, a German organization that produces metal containers and tins. To meet growing demand, the company automated and digitalized its transportation procedures (Blechwarenfabrik, 2023). Researchers have investigated and put-up strategic approaches to gain a more comprehensive understanding of C4.0 and its consequences. These initiatives seek to investigate the present condition of C4.0, address challenges, and delineate strategies for putting it into practice. Malaysia's Construction Industry Development Board (CIDB) has formulated a strategic plan for 2021-2025. This plan aims to boost the usage of current and upcoming technologies in construction projects, focusing on increasing project performance (Smart CIDB, 2023).

Research in this field has explored many C4.0 technologies. Begić (2021) undertook a systematic review of BIM applications in construction projects, emphasizing the impact on coordination, communication, and decision-making processes. In addition to the potential advantages, researchers have highlighted challenges impeding the broader implementation of C4.0 technologies. Although there are notable advancements in C4.0 technology, ongoing challenges must be addressed. Existing research shows an increasing emphasis on comprehending the connection between C4.0 and organizational performance. Additionally, researchers are identifying areas of improvement and potential chances for additional improvements in this field (Das et al., 2022; Forcael et al., 2020; Karmakar & Delhi, 2021; Pham & Dan, 2023). This is partly attributable to the lack of skilled labour to embrace the C4.0 technology. According to the World Economic Forum, construction projects are witnessing a shortage of young talent. In a poll, 50% of general contractors indicated worry regarding recruiting experienced staff. In a survey conducted in the United Kingdom, 45% of construction organizations highlighted "limited access to labour" as a difficulty for the coming year. Additionally, most scientific circles concur that construction projects will continue to rely heavily on professional and unskilled labour in the foreseeable future (Begić & Galić, 2021; Calvetti et al., 2020; Fargnoli & Lombardi, 2020).

Furthermore, the significant potential for transformation that C4.0 possesses is acknowledged. This transformation extends beyond construction projects and has significant socioeconomic implications. As the Board of Engineers Malaysia states, C4.0 impacts different industries that depend on construction projects for advancement and sustainability (Roslan, 2022). Multiple research projects have analyzed the consequences of C4.0 on construction project performance. Interestingly, Turner (2021) examined the impact of robotics and automation on construction productivity. The research identified potential ways to enhance efficiency and reduce costs in project delivery.

2.2 Skills in Construction

Existing research has investigated the changing skill demands within construction projects. Ellison (2023) conducted qualitative research to determine the essential technical and soft skills employers in the contemporary construction industry want. The research highlighted the increasing significance of digital literacy, problem-solving, and communication skills. Research has also examined the impact of training and education programs in preparing project teams with the essential skills to work on construction projects. Hassan (2021) conducted a meta-analysis to assess the impact of vocational training programs on skill development and employment results. The research emphasized the impact of practical learning methods in improving individual skills.

Research has focused on tackling the challenges of developing a trained workforce for construction projects to address problems with attracting and keeping qualified individuals. Existing research also concluded methods for attracting and retaining skilled individuals in construction projects, highlighting the significance of offering competitive salaries, career progression opportunities, and inclusive workplace policies (Mohd Yusoff et al., 2021; Zaki et al., 2012). The research has also examined emerging trends in skill requirements. Pathuri (2020), performed a Delphi analysis to predict future skill requirements in construction projects. The research highlighted sustainable construction methods, digital fabrication, and collaborative problem-solving as crucial areas for skill development efforts.

2.3 Construction 4.0 and Skills

Multiple literature reviews have been undertaken regarding C4.0 and the skills required in construction projects. Two notable examples are the review conducted by Garcia (2020), which synthesized research on the adoption and implications of C4.0 technologies in construction projects, and the meta-analysis conducted by Mansour (2021a) investigated the impact of skill development programs in the construction industry. However, although C4.0 skills are considered one solution to challenges associated with construction project performance, there is still inconclusive evidence regarding the relationship, as existing research does not sufficiently depict the link. Although existing research identified skills that improve construction project performance, C4.0 skills were left out. Existing research has demonstrated the importance of leadership and entrepreneurship skills in enhancing construction project performance (Acheampong et al., 2021; Haaskjold et al., 2020; MARY, 2018; Putra et al., 2020; Rezvani et al., 2020; Saadi, 2020; Shekarian & Parast, 2021)

Nevertheless, although research has demonstrated that skills impact project performance, construction projects have yet to receive much attention. Rather than construction projects, the research focuses on IR4.0 skills and project performance of other project types (Maisiri et al., 2019; Plawgo & Ertman, 2021). Furthermore, existing research has predominantly focused on individual C4.0 theories (Cugno et al., 2021; Park et al., 2015) and theories associated with skills (Tvenge & Martinsen, 2018; Wang et al., 2021). Consequently, the integration of these theories to achieve productivity objectives has been overlooked (Siriwardhana & Moehler, 2023b).

Another rationale for a comprehensive analysis is that modern construction projects must comprehend the intricate relationship between C4.0 skills and project performance. Adopting C4.0 technologies such as Building Information Modelling (BIM), robotics, and data analytics improves project efficiency, productivity, and cost management. Teams can use this skill to enhance resource allocation, take proactive measures to reduce risks, and guarantee the delivery of high-quality deliverables by using precise design and construction processes. Enhanced communication and collaboration, enabled by C4.0 skills, promote more effective stakeholder engagement. Moreover, these skills empower professionals to adjust to technological advancements, supporting sustainability objectives and improving client satisfaction by providing precise cost estimates and practical project schedules. Understanding the significance of these skills not only directs talent growth but also enables construction projects to remain at the forefront of technological advancement and rivalry.

2.4 Review Articles on Construction 4.0 Skills and Project Performance

This section examines existing review articles on C4.0 skills and construction project performance. Table 3 synthesizes the articles, emphasizing limitations and gaps. Additionally, expanding upon the limitations, the table outlines future research directions on C4.0 skills and construction project performance.

Table 3: Summary of existing review articles on Construction 4.0 and proposed future research directions.

Author	Year	Research focus	Limitations	General areas for future research	Focus for future research
Maskuriy et al.	2019a	Performance factors	No investigation on the impact of C4.0 skills on project performance	• C4.0 skills impact on construction project performance • Relationship between C4.0 skills and construction project performance • Strategies to foster a continuous learning culture in construction projects • C4.0 concepts and educational curricula related to construction project performance	• Analyse the direct relationship between C4.0 skills and project performance • Examine the impact of employees with advanced C4.0 skills on project performance • Explore strategies for developing C4.0 skills that maximize technology benefits • Examine approaches to cultivate human-centric C4.0 skills • Enhance educational curriculum to address the evolving needs of C4.0 skills
Maskuriy et al.	2019b	Collaborative growth using ICT	Impact of C4.0 technologies on construction jobs and necessary skills are lacking		
Kozlovska et al.	2021	Technology penetration and project performance			
Santos et al.	2021	Quality and safety improvement	Neglected required C4.0 skills		
Cugno et al	2020	Economic benefits and socioenvironmental gains	No relevancy to C4.0 skills		
Dallasega et al.	2018	Construction supply chain	Overlooked essential human skills related to C4.0		
Alaloul et al.	2018	Sustainable development opportunities	No details on the required C4.0 skills		
Yousif et al.	2022	Sustainability and cost efficiency	No discussion on the required C4.0 skills		
Begic et al.	2021	Project processes empowerment	No outline of the required C4.0 skills		
Khan et al.	2021	Sustainable design	No comprehensive list of C4.0 skills		

The review reveals major knowledge gaps linking C4.0 skills with construction project performance. Although much research has investigated different aspects of C4.0 and its potential implications, there is a lack of comprehensive consolidation, particularly regarding individual skills and their direct impact on project performance. Table 3 presents the research objectives, limitations, and recommended areas for future research based on the reviewed research. The analysis highlights the need for more detailed research on the relationship between C4.0 skills and project performance.

To begin with, although Alaloul (2018) highlighted the opportunities available in sustainable development for C4.0, the research did not specify the required C4.0 skills. This omission paves the way for future research to identify the required skills for a workforce equipped to support sustainability initiatives with C4.0 technologies. Similarly, Dallasega (2018) addressed the construction supply chain but overlooked the required skills for C4.0. This is a critical area for further exploration in understanding the skills needed to manage and optimize technology-driven processes in C4.0, particularly regarding the human element in supply chain efficiency. This understanding is vital for enhancing the overall effectiveness and sustainability of construction projects.

Later, Maskuriy et al. (2019a) discussed individual performance factors related to the construction project but did not determine the impact of C4.0 skills on project outcomes, leaving a knowledge gap. Future research should explore this effect and assess how employees with advanced C4.0 skills impact project performance. It is crucial to develop strategies for cultivating such skills effectively to ensure maximum benefits from integrating technologies and fostering human-centered C 4.0 skills. Additionally, promoting a learning culture that supports continuous improvement in construction projects through educational curricula aligned with the dynamic needs of C4.0 skills is essential.

Maskuriy et al (2019b) also highlighted the importance of collaborative growth through the effective use of C4.0 technologies. However, the research failed to address the impacts of C4.0 technologies on construction jobs and the evolving skill requirement. Future research can investigate how job roles and required skills are being reshaped by the integration of C4.0 technologies in a construction environment. For example, although the research has demonstrated that C4.0 implementation impacted project performance, there is insufficient analysis of the required C4.0 skills for such implementation. This study aims to fill that gap, providing insights into the relationship between C4.0 skills and project performance.

Although Santos (2021) addressed improvements in quality and safety; the research failed to address the required C4.0 skills to achieve such improvements. To address this limitation, future research should identify and highlight the required skills to uphold safety and quality standards within the C4.0 framework. Similarly, Cugno et al. (2021) addressed the economic and socio-environmental benefits of technological developments but did not discuss the relevance of specific C4.0 skills. To fill this gap, future research must integrate the identified benefits with the corresponding C4.0 skills driving these outcomes. This approach can provide a more integrated perspective of how C4.0 skills contribute to achieving economic and environmental goals.

Begić (2021) highlighted the importance of project process empowerment but did not delve into the specific C4.0 skills required. Future research can bridge the knowledge gap by identifying the skills that enhance project processes through C4.0 technologies. Similarly, although Khan (2021) explored sustainable design, the research did not pinpoint a definitive set of C4.0 skills. It is crucial to emphasize and define such skills, as sustainable design relies heavily on the effective use of technologies. Although existing research suggests that different skills impact performance in construction projects depending on multiple factors, there remains a need for clear, specific research into which C4.0 skills most significantly enhance project performance. Additionally, Yousif (2022), addressed sustainability and cost efficiency but did not identify the required C4.0 skills. Therefore, future research should provide a comprehensive overview of the C4.0 required to understand why supporting cost efficiency and sustainability with the right human capacity is essential.

Conclusively, although existing research has underscored the significance of IR4.0 skills in construction project performance and identified relevant skills, there has been limited research focus on the critical role of reskilling and training for performance improvement and overall productivity. Notably, there is a gap in identifying the skills specific to C4.0, understanding their impact on construction project performance, and exploring strategies for their dissemination, such as training programs. These limitations in the current body of knowledge underscore the need for this study. This study aims to comprehensively analyse the potential relationship between C4.0 skills and construction project performance by addressing these gaps and expanding upon existing research. By employing empirical investigation and theoretical analysis, this study aspires to make a contribution to research and practice, enhancing understanding and guiding decision-making regarding C4.0.

2.5 Knowledge Gap and Study Positioning

In the evolving landscape of the construction industry, the integration of game-changing technologies under the umbrella of C4.0 has garnered tremendous attention and contributed to the advancement of the industry. Existing research has provided valuable insights into how technology is enhancing the productivity, safety, and sustainability of construction projects (Oesterreich & Teuteberg, 2016). The research underlines the substantial impact that technologies like Building Information Modelling (BIM), the Internet of Things (IoT), robotics, and big data analytics can have. However, several research also identified challenges, such as seamless integration issues, financial considerations, and skill gaps, which needed to be addressed to realize the potential of C4.0 technologies fully.

Although significant strides have been made in understanding the technological aspects of C4.0, a notable gap persists in research concerning the required skills for effectively applying C4.0 technologies and direct impact on project performance. Existing research has been concentrated on the level of technology adoption rates, overlooking the intricate process involved in skill development and the links between C4.0 skills and key project performance, such as quality, safety, and cost efficiency (Hwang et al., 2022; Mudzar et al., 2022; Turner et al., 2021; Zhi et al., 2022). Furthermore, although some research advocates for continuous learning and skill enhancement, there remains a need for a sufficient understanding of how these skills directly impact into measurable improvement in project performance.

This study addresses a crucial gap by identifying the skills needed to leverage C4.0 technologies and their impact on project performance across various dimensions. Existing research has not fully explored the importance of studying the impact of C4.0 skills on project performance. By aiming to provide a comprehensive analysis, this study seeks to answer fundamental questions related to skill development and propose strategies to enhance the adoption of C4.0 technologies Through a systematic literature review, this study conducted an in-depth analysis of C4.0 skills and their influence on project performance, integrating perspectives from technology and human resource in a novel and holistic approach. This study focuses on elucidating this interaction to provide informative findings for the construction industry. The findings are expected to inform future research directions and practical applications that aim for improved project outcomes and enhanced industry performance.

3. METHODOLOGY

Several methodologies, such as critical literature review, meta-analysis, and systematic literature review (SLR), can be used by a researcher to review the present body of knowledge (Grant & Booth, 2009). The SLR was employed as the methodology for this study. Biolchini et al. (2005), described an SLR as a specialized scientific process designed to acquire and assess the available information on a subject matter. In addition, the value of the SLR depends on what the researchers did, the identified findings, and the review's comprehensibility (Moher et al., 2009). A comprehensive SLR should address the current state, future research priorities, and research gaps of a subject matter (Page, Moher, et al., 2021). Therefore, an SLR is appropriate for establishing the relationship between C4.0 skills and construction project performance, providing empirical insights on the subject matter, and addressing significant gaps.

Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) was adopted to enhance the quality of research articles reviewed. The method's transparency renders the approach and analytical process more straightforward and accurate. Therefore, PRISMA facilitates the generation of evidence-based research and enhances the quality of the review (Shamseer et al., 2015). Moreover, most construction research uses this methodology (X. Chen et al., 2022; Kozlovska et al., 2021; Regona et al., 2022). According to Selçuk (2019), the PRISMA guideline has a four-phased flowchart with the following phases: Phase 1: Identification, Phase 2: Screening, Phase 3: Eligibility, and Phase 4: Inclusions. Table 2 outlines the eight stages incorporated within the four stages to maximize the review's results.

Table 1 outlines the assessment criteria for the SLR in this study. This table includes the principles of exclusion and inclusion, which are used to obtain a precise and relevant dataset for further analysis.

Table 1: Inclusion and exclusion criteria.

Inclusion/ Exclusion Criteria	Criteria Explanation	Results (No. of articles)
Exclusion criteria		
Search Engine Reason (SER)	SER 1: The search engine used was Scopus	168
	SER 2: All searches were limited to research published from 2018 until the current year	
	SER 3: Articles with relevant title, abstract, and keywords in English only	168
		56
Without Full-text (WF)	Articles without full texts	0
Non-Related (NR)	The content is irrelevant with keywords searched	112
Inclusion criteria		
Partially Related (PR)	Search mentioning construction engineering based on the search algorithm was: TITLE-ABS-KEY (("skill*") OR ("competenc*") AND ("industry 4.0") OR ("construction 4.0") OR ("4th industrial revolution") AND (performance)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")).	39
Strongly Related (SR)	Focus on articles related to skills and construction project performance within the context of IR4.0 or C4.0	12
Articles with final requirements achieved	Only articles related to skills within the context of IR4.0 or C4.0 and discuss project performance	Relevant Articles: 50

Table 2: Steps adopted for the systematic literature review.

Steps	Detailed steps
Initial review	The relationship between C4.0 skills and construction project performance
Objective	Find recent developments in the relationship between C4.0 skills and construction project performance
Criteria for considering the research	Articles that used concepts of C4.0 skills or IR4.0 skills through a bibliometric network
Strategy to obtain the research	Research inside one database (Scopus) for articles published in the last 5 years
Eligibility	Articles from journals only
Data collection	Exclusion of repeated articles; read of abstracts; read of full articles; addition of relevant articles that were cited by the initial articles
Quality assessment	Articles analyzed by the authors
Synthesize results	Summary and results of all analyzed articles divided by area of research

Source: Author's own creation.

The flow diagram presents the process adapted to extract data from databases. Figure 1 illustrates the article selected for the SLR through the PRISMA method. First, the article search was performed using the search query, and duplicated articles were removed from the list. Simultaneously, articles not relevant were removed. The subsequent subsections detail each step involved in the SLR.

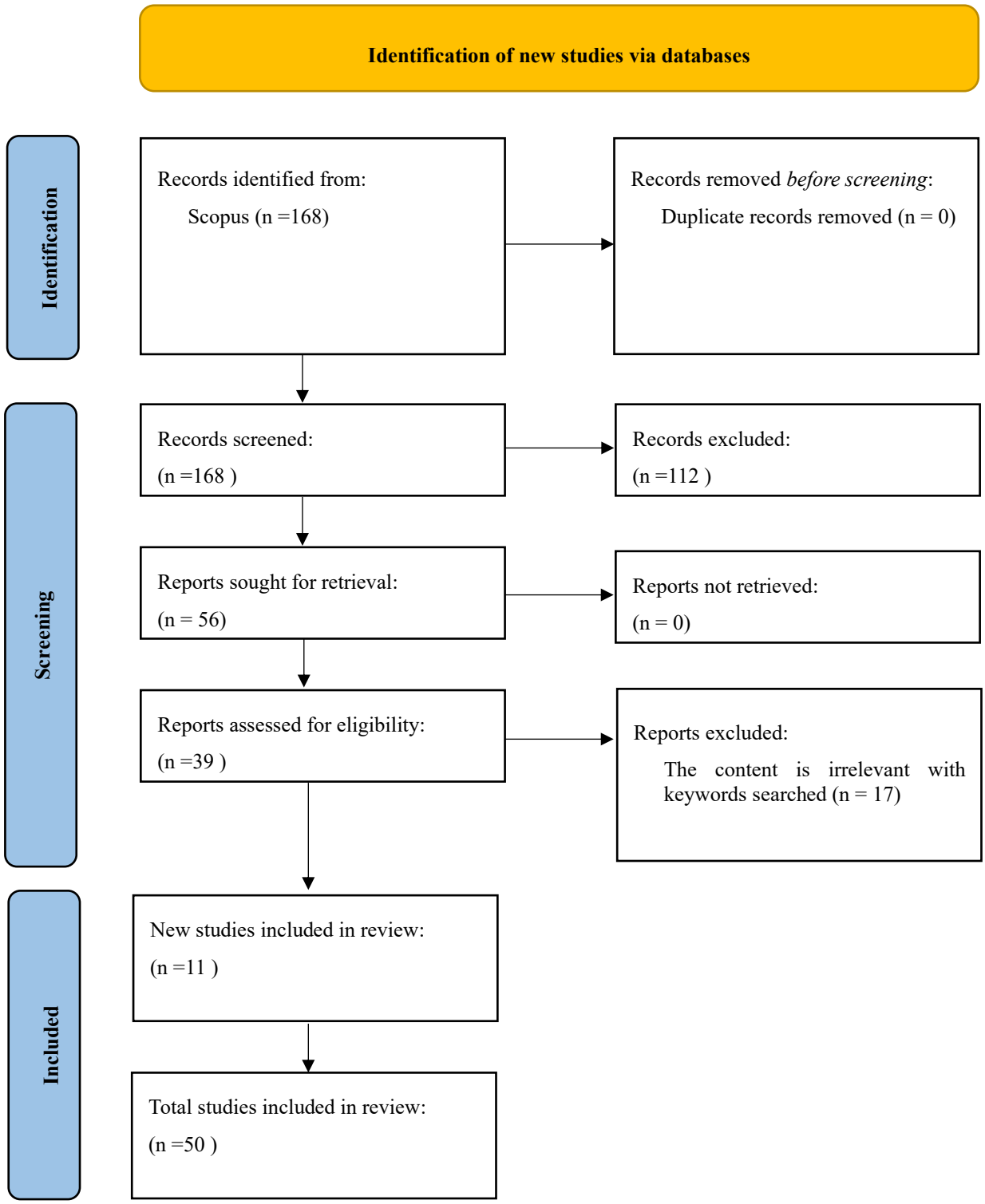

Figure 1: The systematic literature review procedure (PRISMA framework). Source: (Page, McKenzie, et al., *2021).*

3.1 Database Selection

This analysis retrieved the SLR articles from the Scopus database. Scopus has the largest abstract and citation databases; hence, it is widely used for SLRs in construction project management and other disciplines (e.g., engineering, management, and business) (Radzi et al., 2021). This is the case when comparing Google Scholar, Web of Science, and PubMed to other databases. Scopus provides the most exhaustive construction research coverage available (Ghaleb et al., 2022). In addition, since 2004, Scopus has included 15,000 journals from 4,000 publishers and is evaluated annually to guarantee that quality criteria are upheld (Li et al., 2020).

3.2 Article Identification

"Industry 4.0", "Construction," "4.0", "Skills," and "Performance" were used as search terms because the subject matter is new and developing, which may result in a smaller number of articles. In addition, the search was restricted to articles published in English to avoid translation bias. As Palmatier (2018) contends that it is essential for an SLR to rely on high-impact journal articles to synthesize past research effectively and provide a valuable overview of knowledge and concepts, the search was limited to academic journal articles and excluded conference proceedings, book chapters, review articles, and books. The search algorithm was: TITLE-ABS-KEY (("skill*") OR ("competenc*") AND ("industry 4.0") OR ("construction 4.0") OR ("4th industrial revolution") AND (performance)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")). The search was conducted on January 6, 2024. The final search term revealed a total of 168 articles.

3.3 Abstract Screening

During this phase, an in-depth review of titles and abstracts was conducted to find pertinent articles on C4.0 skills and construction project performance. The selection of articles in this stage is essential as it enables the inclusion of only those related to the subject matter and includes the most pertinent information. By exclusively examining articles that address the subject matter, the process guarantees the relevance and high quality of the collected data and insights (Lubbe et al., 2020). After conducting title and abstract screening, 56 articles were chosen for additional analyses using a thorough selection process. The initial phase establishes the groundwork for the subsequent investigation by establishing a substantial repository of pertinent articles for reference.

3.4 Full-Text Screening

A full-text review was conducted at this phase to identify the final articles that met the criteria for further evaluation. Conducting a full-text check is crucial because it enables a more comprehensive assessment of the articles. Here, the articles were identified primarily by examining the title and abstract. This stage guarantees that the articles that have been chosen for further review satisfy the precise criteria for inclusion and exclusion that were established. After reviewing the full texts, 39 articles were deemed suitable for additional analysis. This phase is of utmost importance as it facilitates a more comprehensive analysis of the selected articles and guarantees that the collected data and insights are high quality and relevant to the subject matter (Farouk & Rahman, 2023).

3.5 Snowballing

Similar articles were detected compared to other published SLRs related to C4.0. In a comparable research Maskuriy et al. (2019a), just 10 out of 300 identified database articles were useful. Another example is provided by Maskuriy et al. (2019b) just 20 of the 547 identified articles were included in the final review. In addition, in the research by Franco et al. (2022), 27 of the 113 articles were evaluated. In the same way, Shafei (2022a) analyzed 22 articles. In the meantime, Balasubramanian et al. (2021) provided a complete, multidimensional C4.0 sustainability framework by examining 29 articles. Furthermore, Boton (2021) claimed that few articles on "C4.0" exist in the existing body of knowledge as the subject is still in its infancy and growth.

As an additional measure to identify pertinent articles, forward and backward snowballing methods were implemented in response to the limited number of articles detected during the full-text check (Wohlin et al., 2022). The forward snowballing approach comprised a search of the citations of the identified articles. In contrast, the backward snowballing method comprised a search of the articles' references. 11 additional articles were identified using this approach, increasing the total count of eligible articles to 50. This phase is critical because it enables a

more thorough and all-encompassing review of the subject matter. The snowballing method is frequently employed in existing research to enhance the scope of findings and ensure the study delivers a comprehensive and reliable review of the current state of C4.0 skills and construction project performance.

4. DATA ANALYSIS AND RESULTS

4.1 Overview of Existing Research on Construction 4.0 Skills and Project Performance

This section reviews the highest-impact articles, countries, journals, and author keywords linked to C4.0 skills and construction project performance. This analysis was derived from the 50 articles chosen to understand the subject matter better, identify trends, patterns, areas for further research, and the most influential research in the field.

4.1.1 Year-Wise Analysis

The articles are distributed between 2016 and 2024, as depicted in Figure 2. The annual publishing rate witnessed significant growth from 2019 to 2020 before the pandemic, declined in 2021 due to the pandemic's impact, and is projected to increase again from 2021 to 2023 in the post-epidemic period. Only two articles were published in 2024; the review was completed in early January 2024. Conclusively, the increase in growth can be attributed to the rapid advancement of technology linked to C4.0, the requirement to acquire the essential skills to support C4.0, and the potential advantages in improving performance offered by C4.0 technologies (Shafei et al., 2022a).

The work published in 2016 was regarded as the most often cited and referenced article in IR4.0 skills. Hence, this article is intended to be a main source for summarizing the C4.0 skills and their impact on construction project performance. Moreover, Figure 3 illustrates the bibliographic coupling among the articles, indicating that Hecklau (2016) has the highest citation count. Additionally, Figure 4 illustrates that the co-citation of Hecklau (2016) is very prominent. Therefore, this study also offers valuable perspectives on the intellectual relationships and thematic resemblances across texts, enhancing the analysis of the C4.0 skills.

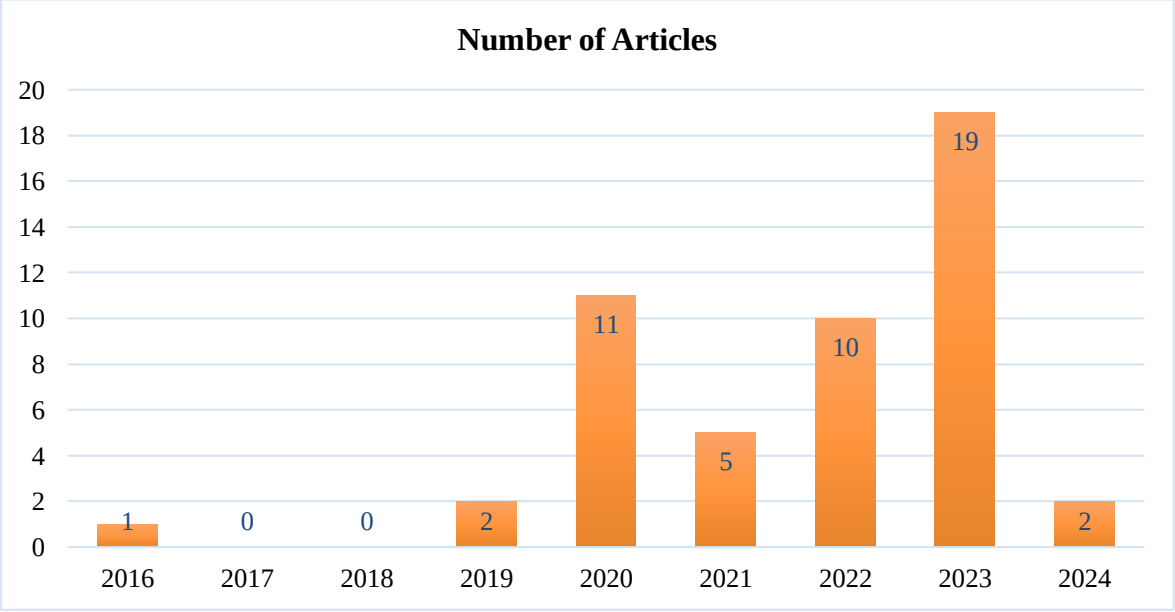

Figure 2: The distribution of selected articles by year.

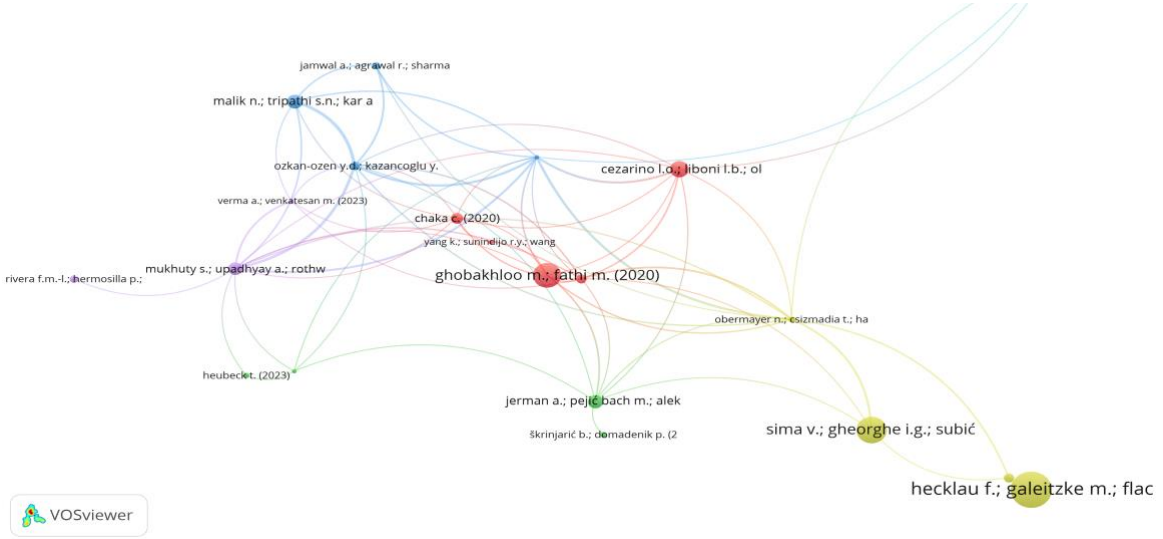

Figure 3: Bibliography coupling among the citations.

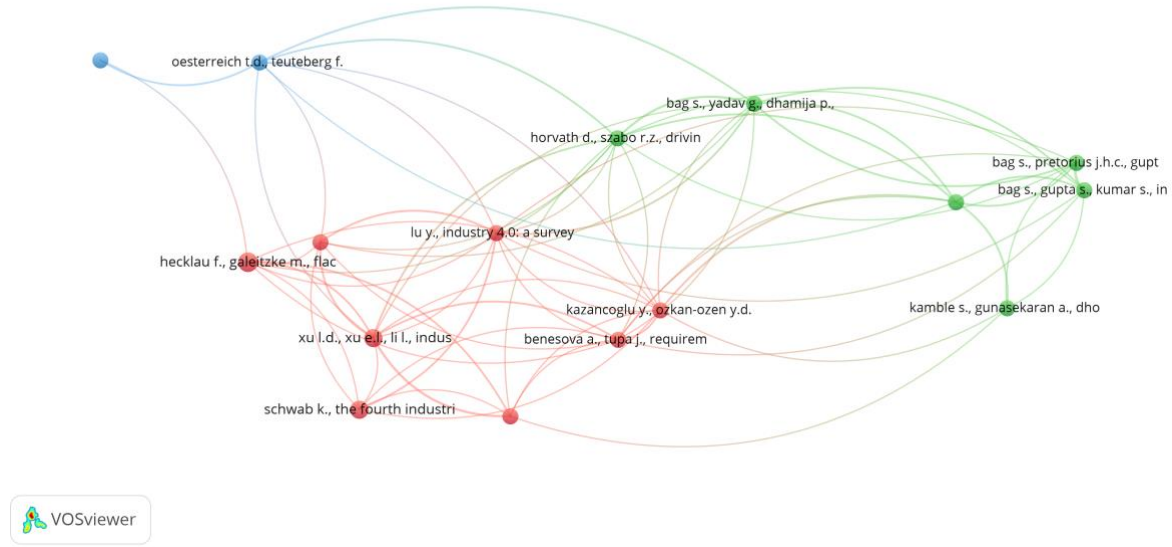

Figure 4: Co-citation among the cited references.

4.1.2 Number of Articles by Country of Lead Author

Regarding the contributing countries, a total of 21 countries made contributions to the body of knowledge, as depicted in Figure 6. India made the highest contribution, with eleven articles, and South Africa and Australia provided four articles each. This can be attributed to their origin in the BRICS countries. The BRICS countries comprise approximately 30% of the Earth's land area, accounting for 45% of the global population. The BRICS countries have consistently been recognized as one of the world's fastest growing and emerging market economies for several years. The primary competitive advantage of this group lies in their cost-effective labour, advantageous demographic characteristics, and ample natural resources during the period of the global commodities upswing. This is a significant indicator because it reveals that these countries have the means to conduct extensive scientific research and publish numerous scholarly research. This aligns with C4.0's goals, as it attempts to boost construction project performance and economic efficiency using new technologies and processes. Lastly, Malaysia, Spain, the United Kingdom, and Hungary have three articles.

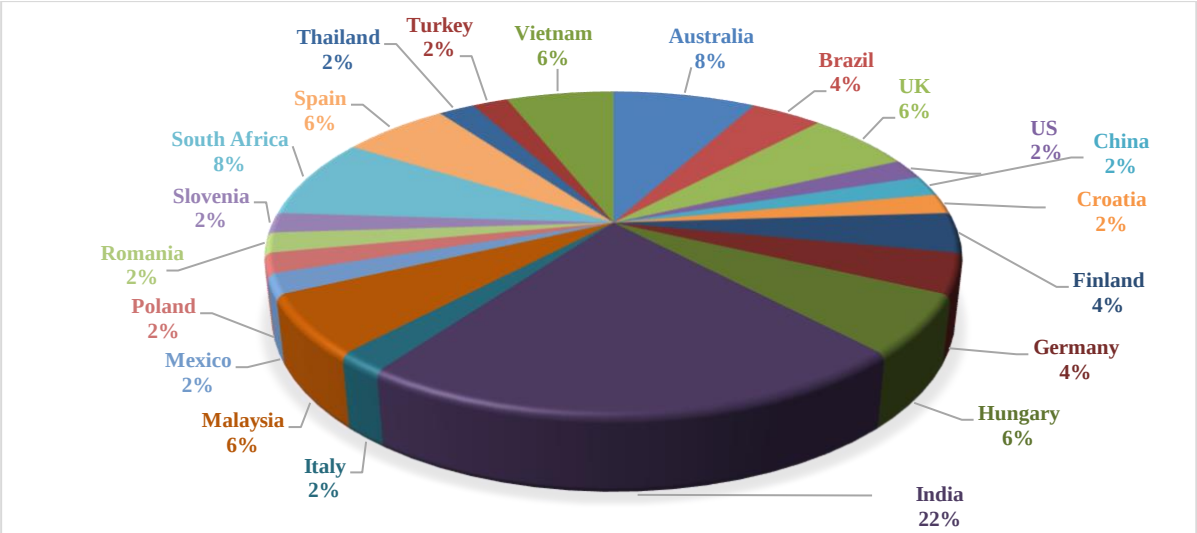

Figure 5: Number of articles by country of lead author.

4.1.3 Keyword Statistics

The network was established using Scopus database-identified articles. The chosen articles were exported as a CSV report for extensive analysis. These data were analyzed using VOS Viewer, a tool for generating and visualizing bibliometric networks (VOSviewerTM, 2023). Using VOS viewer, the authors analyzed the occurrence of keywords to determine which keywords are most prevalent in the selected articles. In research investigations, keywords are one of the most important factors for retrieving relevant fast before reading the articles (Norouzi et al., 2021).

This analysis enhances understanding of the relationships between C4.0 skills and performance ideas. Only **46** of the **363** keywords met the requirement of occurring together in at least two selected articles. The total co-occurrence link strength with other terms was evaluated for each of the 46 keywords. The buzzwords that form the most influential clusters are **IR4.0, skills, and human resource management**. Figure 7 illustrates the most common single-word and two-word keyword combinations in titles, abstracts, and keywords. **"IR4.0"** was the most often mentioned and interlinked keyword, with a total link strength of **91**. The size of each node represents the frequency of its corresponding term, and the linkages depict the relationship between keywords.

C4.0 appeared in the list of identified keywords five times with a total link strength of 12. Figure 7 depicts a strong relationship between C4.0 and skill development, digital transformation, and leadership skills. The review found no discernible correlation between skill in the broad field of C4.0 and performance. However, Figure 8 indicates a definite correlation between operational performance, sustainability, and human resource management in the context of C4.0. The study has identified gaps where additional relevant research is needed to establish a connection between C4.0 skills and construction project performance.

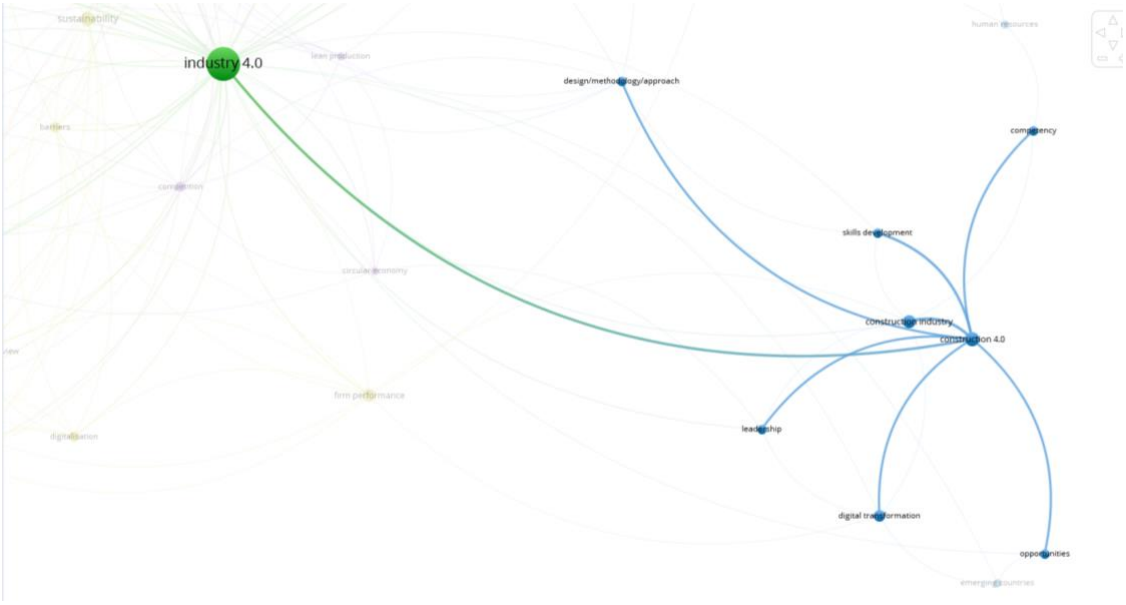

Figure 6: Network of co-occurring keywords (Construction 4.0 cluster).

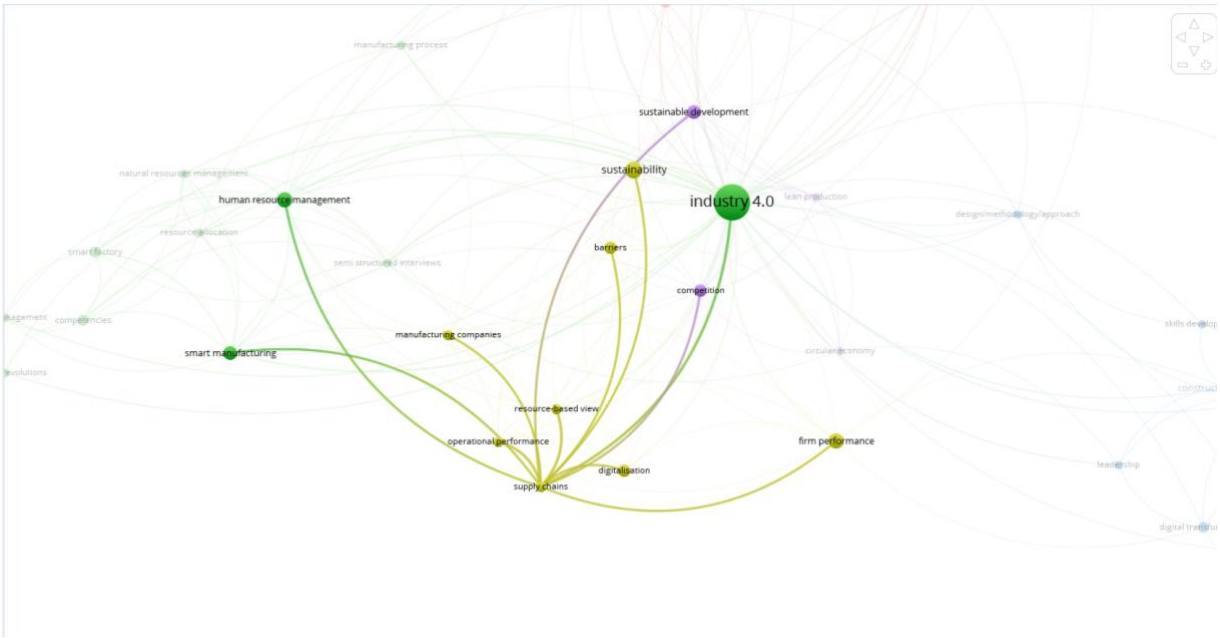

Figure 7: Network of co-occurring keywords (Performance cluster).

4.2 Present Status of Existing Research on Construction 4.0 Skills

Clustering analysis is a method for splitting data items or points into distinct groups and clusters. Clustering, similar to classification, recognizes connected data items; however, unlike classification, the names of the classes are unknown (similar to unsupervised learning). Cluster analysis is widely used in different domains, including data mining, statistics, picture segmentation, pattern recognition, object recognition, data retrieval, computational biology, and others (Chaudhry et al., 2023). Other SLR articles in construction project management have also employed this approach to classify the existing body of knowledge. These articles include the research of Chen (2022), Hossein et al. (2024), Maskuriy et al. (2019b), and Rehan et al. (2024). The clustering methodology

initially gathers different research documents related to C4.0 from different sources. Subsequently, a sequence of preprocessing procedures was carried out to filter and normalize the textual data, guaranteeing its suitability for analysis.

Subsequently, features were derived from the pre-processed textual data, encoding the substance of each document in numerical form. Then, a clustering technique was chosen to categorize similar texts according to the thematic similarities in their content. The emerging clusters provide insights into different aspects of C4.0 research, such as the automation and digitalization of processes, resource management, talent enhancement, performance assessment, and incorporating sustainability into construction practices.

These clusters directly contribute to fulfilling the study aim. The first cluster, which focuses on automation and digitalization (Cluster 1), provides insights into the technical breakthroughs driving C4.0 and their consequences for construction project performance. The resource management cluster, also known as Cluster 2, focuses on the important role of human resource management and skill development in implementing C4.0. It addresses the study aim by identifying the main skills emphasized in different situations. Cluster 3, which focuses on skill development, offers valuable information about the necessary skills for successfully adopting C4.0.

Furthermore, Cluster 4, which focuses on performance, investigates the challenges and opportunities linked to C4.0. This analysis directly addresses the study aim by examining how C4.0 impacts construction project performance. Cluster 5, which focuses on sustainability, investigates how sustainability concepts and C4.0 practices intersect. It identifies areas lacking research and suggests ways to integrate sustainability into construction processes. Collectively, these clusters thoroughly comprehend C4.0 and its consequences for enhancing construction project performance. Below are descriptions of each cluster:

Cluster 1: Automation and digitalization of processes in Construction 4.0.

The theme consisted of 13 items, including keywords such as automation, information technology, digitalization, artificial intelligence, manufacturing, education, human capital, and innovation. This cluster provides a concise overview of C4.0 applications in the present body of knowledge. This cluster primarily focuses on the common domains of discussion in the field of research related to C4.0, with an emphasis on the generalized implementation of these areas.

Cluster 2: Management of resources within the context of Construction 4.0.

The resource management cluster is the most notable in Figure 9, represented by green bubbles with 11 items. This cluster revolves around the diverse resources that must be considered in the context of C4.0, including human resource management, natural resources management, resource allocation, skills, and project management. This cluster is significant as it focuses on Human Resource Management, where skills play a major role (Alhosani & Ismail, 2021). Moreover, within the framework of C4.0, there is an increasing focus on the need to provide individuals with the appropriate skills. The decline in demand for physical and manual skills in repetitive jobs highlights the importance of fostering talents with C4.0 skills. The role of human resource management is crucial in addressing the obstacles that arise from embracing change and equipping individuals with the skills required to meet the changing needs of construction projects (The Straits Times, 2022).

Cluster 3: Skill development in Construction 4.0.

Figure 9 shows that this cluster comprises ten elements represented by blue bubbles. This cluster comprises pertinent and evolving keywords such as digital transformation, leadership, skills development, emerging countries, human resources, and opportunities. This cluster is significant as it highlights the most frequently referenced skill, which is leadership. This skill is relevant not only in the context of IR4.0 but also in C4.0 (Yang et al., 2022). To succeed in the C4.0, organizations related to construction projects must ensure that their workforce is adequately prepared through initiatives focused on upskilling and reskilling. To use C4.0 technologies, it is essential to have a proficient workforce that is capable of effectively using advanced tools and processes (McKinsey & Company, 2022).

Cluster 4: Performance in Construction 4.0.

This cluster comprises eight items depicted by the yellow bubbles. This cluster includes keywords such as barriers, operational performance, resource-based view, supply chains, sustainability, and organization performance. This cluster deserves greater attention, as it embodies the promises of C4.0. The progress made in C4.0 is fundamentally

more sustainable, resulting in alterations to sustainable value chains and manufacturing environments due to digital transformation (Samper et al., 2022). However, despite its tremendous potential, researchers, stakeholders, and project managers need help in effectively integrating C4.0 into construction projects (Mansour et al., 2021).

Cluster 5: Sustainability and Construction 4.0.

Figure 9 shows the cluster of the last four items represented by purple bubbles. This cluster comprises keywords like sustainable development, competition, lean production, and circular economy. Research on the impact of C4.0 and the circular economy on lean production and culture is a developing field. Understanding the impact of C4.0 and circular economy principles on lean leadership and culture offers significant insights for improving production processes (Gatell & Avella, 2024).

Figure 9 illustrates the clustering within the research domain through a keyword network visualization of C4.0, skill, and construction project performance from 2019 to 2024. The terms are clustered into five primary themes, which are discussed in detail in the subsequent subsections.

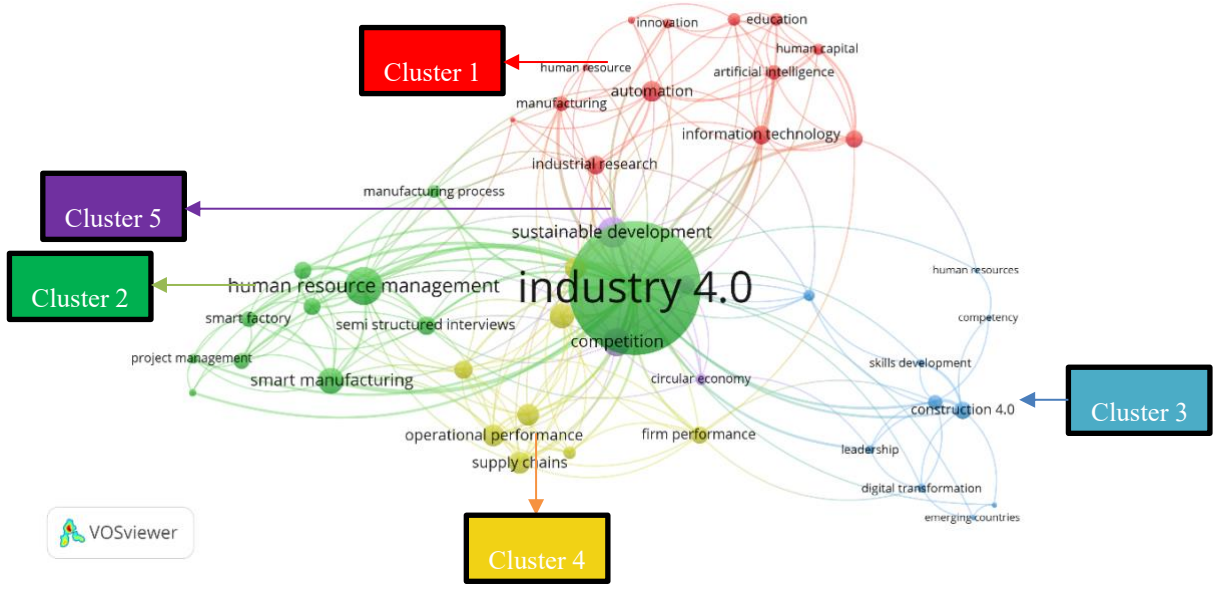

Figure 8: Network visualization of the keywords.

4.3 Present Status of Existing Research on Construction 4.0 Skills and Project Performance

Existing research has attempted to outline the combination of skills necessary for implementing IR4.0 across different project types (Kaufmann et al., 2018). Nevertheless, most of these advancements are grounded in national circumstances and current research on the comprehensive adoption of IR4.0 across several project types, including construction projects (McHugh et al., 2022). Due to several factors, Hecklau's (2016) research stands out as a foundational starting point for the skill matrix. Hecklau's (2016) research provides a comprehensive analysis of the diverse skills required for good project performances, including a broad spectrum of skills critical for human resource management in the era of IR4.0. The skills are meticulously classified into distinct categories, establishing a structured framework that promotes understanding and implementation. Furthermore, his work is backed by empirical research and industry expertise, which enhances the credibility of the skills that have been identified and their applicability to practical project circumstances. Additionally, Hecklau's research received the highest citations during the review, suggesting that it is widely acknowledged and embraced in the academic community. This finding additionally supported the credibility and validity of employing Hecklau's (2016) work as the foundation for the skill matrix, highlighted in section 4.2.

Mapping skills from other articles into Hecklau's framework includes careful review and evaluation. By comparing skills identified in other research to Hecklau's categories, descriptions and requirements are sought. By integrating identified essential skills from multiple sources into a unified framework, this mapping process prevents redundancy and guarantees broad coverage. Furthermore, it facilitates the detection of gaps or inconsistencies in the current body of knowledge, thus guiding the development of future research. For example, when mapped onto Hecklau's (2016) framework, skills such as effective communication, adept conflict resolution, and proficient risk management contribute to enhanced stakeholder engagement, collaborative teamwork, and overall project performance. As every identified skill was evaluated based on relevance and importance in enhancing project performance, this process ensured that the resulting skill matrix encompassed the fundamental skills necessary for effectively managing the opportunities and threats that arise from C4.0.

In addition, different research has demonstrated using Hecklau et al.'s (2016) skill model framework to classify construction skills. For example, Kannan (2021) proposes using Hecklau et al.'s methodology to identify skill gaps systematically. This technique facilitates understanding of the precise skills needed in the construction business and assists in mitigating potential deficiencies in skills. In addition, Torres (2023) investigated jobs and skills crucial for C4.0, which refers to incorporating advanced technologies into construction processes. This characterization includes the classification of skills, using frameworks like Hecklau et al.'s model to thoroughly grasp the skill landscape in construction projects.

Furthermore, the analysis of forthcoming proficiencies in IR4.0, as explored by scholars Hecklau and Janis (2017; 2018) frequently entails classifying proficiencies into separate categories, such as technical knowledge, methodological skills, social skills, and personal skills. Categorization frameworks are crucial in defining the skills required to manage project changes. In addition to evaluating individual skills, existing research (e.g., Rodzalan (2022) employs classification frameworks comparable to Hecklau et al.'s model. These frameworks are used to determine the degrees of skills and identify elements that contribute to skill inadequacies. Moreover, several authors, including Chaka (2020), da Silva et al. (2022), Macpherson et al. (2022), Nguyen (2022a), and Oosthuizen (2022), have contributed valuable insights by discussing ongoing research projects or published research using Hecklau's framework for skill assessment. This study sheds light on the practical application and effectiveness of Hecklau's framework in different contexts, providing further validation and refinement of its utility as a tool for understanding and evaluating skills within different domains. Table 4 summarizes the study findings, and the subsequent subsection discusses the skills derived from the categorization.

4.3.1 Technical

According to Table 4, technical skills were the most frequently cited skill. Technical skill refers to the comprehensive technical expertise required to transition from operational to strategic duties. Technical skills are essential for satisfactorily carrying out job duties, responsibilities, and tasks. However, based on the research conducted by Ismail (2019) and an examination of existing research and interview results, it is indisputable that a disparity exists between the present technical skills and those mandated by C4.0. Hussain (2020) concurs that construction projects require new categories of highly trained personnel with expertise in particular domains.

Likewise, the research has yielded technical skills such as digital leadership via soft skills, lean and agile project management, and BIM skills, among others (Gledson et al., 2024). These skills collectively facilitate the digital transformation of construction projects, incorporating innovative technologies such as artificial intelligence (AI), robotics, 3D printing, and machine learning. This finding is consistent with the results reported by Rodzalan (2022), who also compiled a list of technical skills required for C4.0. That list included the skills to analyse, model, program, and employ collaborative robots, employ additive manufacturing technologies, simulate, design, and construct digital supply networks, manage large amounts of data, and implement IT architectures, platforms, and component orientation in the direction of C4.0.

4.3.2 Methodological

Methodological skills encompass every talent and skill necessary for making decisions and addressing problems in general. Independently, consciously, and with previously learned thinking and working skills, methodological skills equip individuals to tackle novel and challenging challenges (Yu et al., 2021). In the same way, the CIDB Malaysia (2020) Strategic Plan underscores the need to align skills with C4.0. It emphasizes the significance of personal and interpersonal skills, such as problem-solving. The impact of C4.0 on the labour force highlights the

dualistic nature of its consequences, wherein a need for new skills complements increased productivity. Within this setting, the skills to solve problems become an essential skill to tackle and overcome constantly evolving responsibilities and challenges effectively. Existing research indicates that problem-solving is one of the most important C4.0 skills. To effectively manage the complexities offered by C4.0 technologies, the workforce must possess essential skills such as critical thinking, creativity, and analytical capacities. Skills such as decision-making and conflict-solving are crucial in Industrial Revolution 4.0, emphasizing the significance of solving problems.

Furthermore, analytical skills are vital in the era of C4.0, characterized by the integration of digital technology and data. The C4.0 Strategic Plan (2021-2025) emphasizes the significance of aligning skills with C4.0, particularly in data analysis and visualization. The plan highlights the importance of developing expertise in digital twin technologies, modeling, and simulation, IoT and sensor data integration, cybersecurity, and artificial intelligence/machine learning. These areas of focus necessitate a strong aptitude for analysis. Existing research highlighted the importance of analytical thinking in making important decisions, particularly in complex projects related to C4.0 technology. The assessment results on skill gaps in C4.0 indicate that professionals in the field must possess advanced analytical skills to tackle the problems brought about by technological breakthroughs effectively (Shafei et al., 2022b).

4.3.3 Social

Social skills include communication, collaboration, leadership, emotional intelligence, and other skills. Communication skills and teamwork were ranked as the second most cited skills. Effective audience speaking, clear written communication, interaction with individuals from diverse backgrounds, presentation delivery, idea expression, attentive listening, and providing constructive feedback are all communication skills derived from this. Effective communication between humans and machines that enable data-driven optimization is a critical component of many C4.0-related theories, including the Internet of Things, smart cities, and digital building ecosystems. These theories emphasize the significance of communication skills as they facilitate network perspectives and the widespread standardization of such operations (Siriwardhana & Moehler, 2023a).

Furthermore, communication skills were emphasized in the policies deliberated upon by countries such as the United States. The O*NET database was also heavily cited as an indispensable reservoir of occupational information necessary for various professions (Pauceanu et al., 2020). Germany subsequently ratified the European Union's European Skills Framework (ESCO), comprised of European Skills, Qualifications, and Occupations (Akyazi et al., 2020). Furthermore, to tackle skills deficiencies and scarcities in the BRICS countries (Brazil, Russia, India, China, and South Africa), a framework was developed on IR4.0 skills (World Economic Forum, 2018). In all the different national frameworks examined, communication skills consistently occupied the highest position in ranking skills.

Further, the construction project delivery process is marred by a significant degree of fragmentation, coordination, and cooperation deficiencies, all of which impede the formation of effective teams and contribute to project management inefficiencies. Collaboration and teamwork significantly impact project performance as project members must collaborate closely to capitalize on the strengths, compensate for any shortcomings, and fully realize the advantages that can be gained from teamwork (Yap et al., 2020). The transition to C4.0 will result in a reconfiguration of the team structure. Teams will expand in size, diversity, and virtual composition as highly skilled specialists deconstruct difficult and complex projects.

Moreover, C4.0 results in construction projects that are more diverse, with inventive, conventional, and creative employees (Shet (2021). As a result, successful collaboration among disparate individuals is more complicated, and ensuring that the team operates efficiently is more difficult. To surmount the obstacle, Shet (2021) proposes compelling evidence of the critical human capital that can be leveraged with the 4IR. Additionally, C4.0 requires project members to engage in virtual collaboration. Numerous virtual tools are presently employed in construction work environments to facilitate quicker and more efficient communication among individuals, irrespective of their physical locations (Chowdhury & Murzi, 2020).

4.3.4 Personal

An individual's skills consist of their social values, goals, attitudes, and perspectives on life. These skills are personal and hard to quantify or teach (Hecklau et al., 2017). In contrast, the skills identified the least were compliance and ambiguity tolerance, which belong to this category. Currently, the study primarily emphasizes

technical skills, including those that are directly associated with digitalization, automation, and the usage of C4.0 technology. However, existing research may not prioritize these personal skills. However, the skills may be considered essential. Certain skills, including compliance or communication skills, may be assumed to be fundamental or implicitly included in broader skills frameworks. Another reason is that certain notions or principles are regarded as fundamental or implicit in the context of C4.0, and researchers may need to include them in their research explicitly.

Table 1: List of Construction 4.0 skills extracted from existing research.

Skillset	Skill	(Hecklau et al., 2016)	(Malik et al., 2022)	(Bag et al., 2024)	(Siriwardhana et. al, 2023)	(Heubeck, 2023)	(Kissi et al., 2023)	(Aranda-Jiménez et al., 2023)	(Chin, 2021)	(Vinodh & Wankhede, 2020)	(Yang et al., 2022)	(Souza & Debs, 2023)	(Marnewick & Marnewick, 2020)	(Pawel Poszytek, 2022)	(Rivera et al., 2020)	(Jerman et al., 2020)	(Nguyen, 2022a)	(Tran et al., 2023)	(Le et al., 2020)	(Chaka, 2020)	(Škrinjarić & Domadenik, 2020)
Technical	State-of-the-art knowledge	✓													✓	✓	✓		✓		
	Technical	✓		✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Process understanding	✓			✓		✓	✓				✓	✓							✓	
	Media	✓					✓	✓		✓			✓							✓	
	Coding	✓						✓		✓		✓									
	IT security	✓			✓			✓		✓										✓	
Methodological	Creativity	✓	✓		✓				✓				✓		✓	✓	✓		✓	✓	
	Entrepreneurial thinking	✓			✓	✓														✓	
	Problem-solving	✓	✓	✓	✓		✓		✓		✓		✓			✓	✓	✓	✓	✓	
	Conflict solving	✓	✓		✓		✓		✓		✓		✓			✓	✓			✓	
	Decision making	✓	✓		✓		✓			✓	✓	✓	✓			✓	✓			✓	✓
	Analytical	✓	✓	✓	✓				✓	✓	✓		✓		✓	✓	✓		✓	✓	
	Research	✓			✓															✓	
	Efficiency orientation	✓	✓							✓	✓						✓				
Social	Intercultural	✓							✓				✓								
	Language	✓															✓		✓	✓	✓
	Communication	✓	✓		✓		✓		✓		✓		✓	✓	✓	✓	✓	✓		✓	✓
	Networking	✓					✓					✓								✓	
	Teamwork	✓	✓		✓		✓				✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

Personal	Compromising and cooperative	✓			✓		✓				✓			✓	✓		✓	✓	✓	✓				
	Knowledge sharing skills	✓									✓													
	Leadership	✓	✓		✓	✓	✓		✓		✓	✓	✓					✓			✓	✓		
	Flexibility	✓			✓						✓							✓			✓	✓		
	Ambiguity tolerance	✓									✓													
	Motivation to learn	✓	✓		✓	✓				✓	✓	✓		✓	✓	✓					✓	✓		
	Working under pressure	✓				✓								✓								✓	✓	
	Sustainable mindset	✓				✓						✓		✓								✓		
	Compliance	✓																						

4.4 Future Research Directions for Construction 4.0 Skills and Project Performance

According to Table 4, existing research illustrates that skills impact construction project performance based on numerous factors. However, existing research does not explicitly state the veracity of C4.0 skills that improve construction project performance. Existing research has argued that IR4.0 skills play a significant role in construction project performance and has even identified relevant skills. In contrast, limited research has addressed the significance of reskilling and training to improve performance and overall productivity. Nevertheless, existing research focused more on the significance of reskilling in C4.0 adoption than on identifying the skills pertinent to C4.0 and their impact on construction project performance and how to diffuse them (e.g., training). Moreover, one thing is unquestionable: skills are required to improve project performance regardless of project type.

To advance the understanding of C4.0 skills and their impact on project performance, several themes are recommended for future research. These themes are vital for meeting the diverse requirements of various construction projects and understanding the long-term implications of training in C4.0 skills. One promising area is conducting comparative research across the different types of projects. This approach aims to identify knowledge gaps within the C4.0 skill domain accurately (Sander & Souza, 2023). Such research can pinpoint which types of projects require specific C4.0 skills. For example, infrastructure projects may require different C4.0 competencies than residential or commercial construction projects. Mapping these requirements can enable researchers to make informed recommendations for skills development programs and ensure that the workforce is well-prepared to meet the various project demands.

The next future research theme focuses on the long-term impact of C4.0 skills training on project performance. Collecting relevant data on how skill enhancements impact project performance is crucial. For example, Adhvaryu et al. (2023) suggest that tracking the progress of individuals and teams who have undergone C4.0 training over several years can provide meaningful insights and reveal clear trends and patterns. Such research could involve measuring changes in efficiency, quality, and safety, thus establishing robust evidence for the benefits of sustained training efforts.

Moreover, establishing a more reliable method to measure the impact of C4.0 skill acquisition on project performance is essential. Currently, there is a noticeable gap in measuring the proficiency and impact of C4.0 skill development. Introducing standardized evaluation metrics would ensure consistent assessment and facilitate meaningful comparison. These metrics could encompass time savings, error reduction, and cost savings from applying C4.0 technologies. Implementing such metrics can provide a foundation for precisely and meaningfully measuring the effectiveness of training programs and their outcomes.

Lastly, future research can explore the optimal policy and management strategies that foster the widespread adoption of C4.0 skills in developing countries. The construction industry in these countries often faces unique challenges, such as limited access to cutting-edge technologies and inadequate training infrastructures. Identifying policies and management practices can better integrate C4.0 skills and technologies, increasing project performance and competitiveness in developing markets. Sawhney et al. (2020) share similar ideas. Conducting similar research across various developing countries using case studies can reveal successful strategies and lessons learned.

In conclusion, future research on C4.0 skills and project performance should prioritize these key focus areas to effectively integrate C4.0 technologies in the construction industry. Building on the contributions of this study, further research can delve deeper into enhancing the role of C4.0 skills in improving construction projects outcomes. Such efforts are essential for advancing the industry and driving improvements to improve productivity, safety, and sustainability. The future direction for C4.0 skills and construction project performance is outlined in Table 5.

Table 2: Future directions for Construction 4.0 skills and construction project performance.

Limitations on Existing Research	General Areas for Future Research	Focus for Future Research	The importance of addressing these limitations
Overlooked the contribution of C4.0 skills on construction project performance (Maskuriy et al., 2019a)	**Impact of C4.0 skills on construction project performance** Investigate technical and non-technical skills that significantly impact construction project performance. **C4.0 Skills as moderator/mediator** Assess the correlation between C4.0 skills and construction project performance. **Role of C4.0 skills in technology usage** Evaluate how skills impact the effective usage of C4.0 technologies and explore strategies for skill development to maximize technology benefits. **Strategies to foster a continuous learning culture in construction projects** Prioritize strategies to motivate professionals to remain current with technological improvements and seamlessly integrate new skills into their work practices. **Enhancement of educational curriculum** Analyse the incorporation of C4.0 concepts into educational curricula for construction-related fields.	Examine the direct relationship between C4.0 skills among the workforce and construction project performance. Analyse the impact of employees with advanced C4.0 skills on enhancing efficiency, minimizing errors, and achieving overall project success.	It avoids disregarding critical determinants of project performance and C4.0 skills.
		Examine approaches to cultivate human-centric C4.0 skill development.	Recognize how certain skills impact project performance and allow accurate project evaluations. Ensure construction professionals possess technical and interpersonal skills necessary in the C4.0 era.
Understand the relationship between construction productivity growth and individual enthusiasm without considering actual C4.0 skill levels (Kozlovska et al., 2021)		Examine deficiencies in C4.0 skills among individuals.	Create focused training initiatives to bridge skill gaps.
Explored the impact of C4.0 technologies without exploring C4.0 skills (Dallasega et al., 2018)		Update academic programs to ensure students are equipped with the requisite C4.0 skills.	Having competent individuals is key to good project performance.
Evaluated C4.0's significance but did not provide a comprehensive list of C4.0 skills (Khan et al., 2021)		Examine the long-term impact of ongoing learning initiatives and professional development programs on C4.0 skills. Evaluate the efficacy of several learning models, including microlearning, online certificates, and immersive training experiences,	Ensure projects go well by improving the required skills regularly. Ensure construction professionals remain up-to-date with technology changes

5. DISCUSSION

5.1 Existing Research on Construction 4.0 Skills and Project Performance

The purpose of this review was to conduct a comprehensive assessment of the relationship between C4.0 skills and construction project performance. This area of C4.0 skills has been the point of contention over the past several years. Fifty articles were extracted and analyzed using bibliometric and scientometric analyses. The potential relationship between C4.0 skills and construction project performance has been identified. However, no existing research has validated the relationship. The C4.0 present status is strongly associated with emerging trends and research directions. C4.0 is characterized by significant changes, such as the introduction of programmable logic, reflecting the impact of C4.0. The review highlights the importance of a skilled workforce that can adapt to C4.0. This involves investigating the use of advanced technologies and their practical applications in construction

projects, offering valuable insights into emerging patterns and prospective avenues for growth. In other words, the term C4.0 skills is still relatively new, and as a result, there is not much available research discussing C4.0 skills in depth. Nevertheless, this study has found and described how IR4.0 skills significantly improve performance in other project types.

Regarding C4.0 skills, existing research highlighted the impact of IR4.0 skills on project performance (not specific to construction projects) and, eventually, organization. The most frequently cited IR4.0 skills are technical, communication, teamwork, problem-solving, analytical thinking, and decision-making (L. B. P. P. da Silva et al., 2022; Macpherson et al., 2022; Maisiri & Van Dyk, 2021; Nguyen, 2022b; Peña-Jimenez et al., 2021; Shet & Pereira, 2021). However, the research does not explain how the skills impact construction project performance. On the contrary, existing research discussed the required skills in construction projects, but the focus was on the skills of project managers rather than C4.0 skills. Problem-solving, communication, and teamwork are examples of the discussed skills (O. O. Adepoju & Aigbavboa, 2021; Castro et al., 2022; Cugno et al., 2021; Kissi et al., 2023; Ngo & Hwang, 2022; Shekarian & Parast, 2021; Siriwardhana & Moehler, 2023a).

It was hypothesized that skills have always impacted construction project performance, but there is no supporting evidence as construction projects move toward C4.0. Hence, future research on C4.0 skills and construction project performance should examine the relationship in greater depth. The present analysis indicates that C4.0 skills are beginning to permeate construction projects as the boundaries between different scientific disciplines become increasingly porous. This has broader implications for the C4.0 concept itself. These ideas introduce a new factor and redefine construction projects. Although construction projects traditionally have poor project performance, the analysis indicates that C4.0 skills may change the situation, and this shift is anticipated to accelerate soon.

These findings are consistent with those of other comparable research that indicates C4.0 brings significant benefits to the management of engineering and construction projects (Anil Sawhney et al., 2020; Craveiro et al., 2019; Mudzar et al., 2022; Zabidin et al., 2020). In addition, the trend of articles identified in this review suggests that construction projects need to be provided with C4.0 adoption strategies instead of merely discussing the benefits and challenges. Moreover, these approaches should not be restricted to just one discipline but include all construction players with an active role in the C4.0 era, including their deployment of available technologies and tools.

Wrapping up, this study offers a comprehensive overview of C4.0 skills and their existing state in scientific research. Particularly focusing on their impact on project performance. The findings address the gaps identified in existing research, highlighting the required C4.0 skills for contemporary modern construction projects. The practical implications of these skills were discussed, and future research areas were suggested. Although the current body of knowledge on C4.0 skills is extensive, it is also fragmented. Additionally, despite the wealth of research is available on various technologies and skills related to IR4.0, there remains a need for a well-defined framework for C4.0 skills.

The study provides a comprehensive overview of existing research by consolidating the dispersed data to highlight crucial C4.0 skills in construction project management, including soft skills and hard skills. These findings address the previously unclear identification of relevant C4.0 skills and their impact on project performance. Unlike existing research that lists skills without specifying their relevance to C4.0 or their direct enhancement of construction performance, this study provides critical insights and identifies areas for further investigation. It emphasizes the need for longitudinal research to measure the long-term impacts of C4.0 skills training by using standardized measures to assess skill development and project performance. This approach responds to the current gap in effectively deploying these skills in the construction industry beyond acknowledging the importance of reskilling and training in general. The recommendations for future research can provide a clear plan to address existing gaps and advocate for ongoing skill development and the implementation of industry-wide standards.

5.2 Relationship between Construction 4.0 Skills and Project Performance

The optimization of construction project performance is significantly contingent upon the development and application of diverse skills. Technical skills, including up-to-date understanding and expertise in construction methodologies, are essential for optimizing project planning and implementation (Mudzar et al., 2022). For instance, a thorough grasp of contemporary technologies and methodologies empowers construction professionals to optimize workflows, reduce errors, and increase productivity. Additionally, adequate technical skills enable the

successful integration of automation and Building Information Modelling (BIM) technologies, resulting in enhanced resource allocation and project coordination (Hecklau et al., 2016). Furthermore, research has shown that technical skills benefit the quality and safety of projects. According to Kannan (2021), technical skills are significant in carrying out construction operations precisely and ensuring adherence to safety norms and laws. Construction experts may improve the quality of work and decrease the chances of accidents on-site by following established guidelines and using technical skills.

Methodological skills, such as creativity and sound decision-making, enable project teams to generate new ideas and efficiently address challenges, enhancing productivity and efficacy (Aranda-Jiménez et al., 2023). Creative thinking promotes the development of novel solutions to complicated challenges. In contrast, proficient decision-making empowers project managers to make well-informed selections that are per the successes and limitations of the project (Heubeck, 2023). By cultivating an environment that promotes innovation and proactive thinking, individuals can adjust more easily to unanticipated challenges and take advantage of developing prospects, improving construction project performance. On top of that, research indicates that creativity and effective decision-making are tightly linked, as persons with creativity generally exhibit remarkable decision-making skills (Balconi et al., 2024). Organizations can foster different viewpoints and concepts by promoting creativity within project teams. This can result in more effective decision-making processes and improved project results.

According to research by Chin (2021), effective leadership and communication foster collaboration and team cohesion, providing motivation and direction, and thereby facilitating good project performance. Effective communication skills promote information interchange among individuals involved in a project, diminishing the probability of misinterpretations and disputes (Vinodh & Wankhede, 2020). Moreover, skilled leadership cultivates an atmosphere of confidence and dedication among team members, thereby establishing a constructive professional setting in which every individual is motivated to exert maximum effort. Construction projects can attain superior performance and overcome challenges more efficiently by implementing visionary leadership and facilitating open communication channels. Leadership and communication are intimately linked, as great leaders are often skilled communicators (Arendt et al., 2019). Leaders may establish strong connections with team members, develop trust, and promote a shared sense of purpose by acquiring expertise in communication strategies such as active listening, empathy, and persuasion. Leaders may effectively express project objectives, seek stakeholder input, and gather support for initiatives, enhancing construction project performance.

In addition, research conducted by Souza & Debs (2023) demonstrates that personal skills such as initiative to learn and adaptability empower project teams to endure challenging conditions and sustain productivity. A robust drive for knowledge fosters ongoing enhancement and professional growth, guaranteeing that project teams maintain the required skills for industry development and optimal methodologies. In contrast, flexibility empowers individuals to promptly adjust to changing priorities and limitations, thereby reducing the adverse impact of unanticipated disruptions on project schedules and financial resources. Construction organizations have the potential to optimize construction project performance by cultivating an environment that values continuous learning and encourages adaptable conduct, which in turn strengthens their resilience and agility (Marnewick & Marnewick, 2020). Furthermore, research indicates that initiative and adaptability are strongly connected, as those with one trait often demonstrate the other (Uhl-Bien & Arena, 2018). Organizations may empower their workforce by cultivating a culture that appreciates and promotes these qualities. This empowerment enables employees to proactively tackle emergent problems, seize new opportunities, and easily adjust to changing project dynamics.

5.3 Limitations

Despite great efforts, this study has several limitations. First, the review concentrates exclusively on C4.0 skills and construction project performance trends. Hence, this study cannot represent other C4.0-related research areas. The second limitation is that Scopus was used to conduct article searches. As a result, some articles indexed by other databases might be excluded. Despite this, construction project management researchers frequently use the chosen database for SLRs, enabling the methodology to be acceptable. Third, the search keywords or combinations used to find C4.0 skills are not exhaustive. In addition, electronic databases have search syntaxes that respond optimally to certain keyword combinations but not others (Alammary et al., 2019). Considering this, multiple combinations of search strings were used to derive optimal search results from each of the specified databases. Fourth, only journal articles were included in the review. When seeking information on C4.0 skills for this review, the researcher discovered that grey literature also provided information on C4.0. However, the decision to

concentrate solely on journal articles was made to limit the study's scope by using journal articles as a defining variable. Despite these limitations, the study's objective was adequately achieved.

5.4 Implications

5.4.1 Theoretical Implications

In terms of theoretical contribution, this study offers a profound insight into the relationship between C4.0 skills and construction project performance. The analysis of existing research provides a theoretical framework that integrates various perspectives on how C4.0 functions. The findings can assist researchers and practitioners in identifying areas that warrant further investigation, such as the mechanisms by which C4.0 skills enhance project performance. It also highlights the limitations of the existing research and identifies potential areas for future research to understand better the long-term impacts of C4.0 on construction project performance. Furthermore, integrating the study findings into a single framework can help form new theories that can encompass the dynamic field of construction project management in the digital age.

5.4.2 Practical Implications

The practical relevance of this study is staggering for industry professionals. The study findings demonstrate a clear direction toward human capital training in the construction industry, especially as projects evolve to meet market needs. Therefore, by developing decision-making skills, practitioners can increase the efficiency of the decision-making process and the effectiveness of projects. The study also offers a starting point for comparing the level of organizational capabilities to the benchmark and understanding the gaps that need to be worked toward the practical application of measures that can strengthen C4.0 technology adoption. More importantly, the emphasis on practical implications stresses the need for continuous learning and implementation of professional standards, including proactive approaches to acquiring technologies that would enhance efficiency in the accomplishment of projects and, ultimately, the competitiveness of the construction industry.

5.4.3 Managerial Implications

In this line, the present analysis calls for attention to strategic management as a prerequisite for enhancing the usage of C4.0 technologies among policymakers and other organizational decision-makers. Effective talent acquisition, retention, and investment policies on C4.0 skills are essential for organizations to meet the demands of contemporary constructions. It also gives insights into the policies that must be developed to enhance innovation and adopt newer technologies to remain relevant. Also, the study focuses on the need to integrate effective human resource management techniques and practices that support technological and organizational development within the line of the project performance and continuity.

6. CONCLUSION

Conclusively, this study investigated the current state of scientific research on C4.0 skills and construction project performance. For a project to go smoothly, project members must be skilled in digital tools, BIM, data analytics, and other skills related to C4.0 technologies. In this example, the author explains how advanced technologies and digitalization must be integrated into C4.0 and how C4.0 skills play a major role. However, the term "C4.0 skills" is still relatively new in the current body of knowledge. As a result, there is limited research that investigated these skills in detail. However, this study found and discussed how IR4.0 skills boost performance in other project types. Moreover, safety and environmental concerns positively link C4.0 skills and construction project performance. The technologies that are part of C4.0 are meant to make the workplace safer and encourage a more environmentally friendly way of doing construction projects. However, no explicit research links C4.0 skills and construction project performance. Again, this study is focused on learning new skills to use C4.0 technologies. These are the findings for the first research question.

The second research question focuses on the key skills necessary to implement C4.0 successfully, emphasizing enhancing construction project performance. The technical skills encompass computer literacy, communication, teamwork, problem-solving, analytical thinking, decision-making, and other related skills. These skills enable professionals to manage the intricate details of sophisticated technology, interdisciplinary collaboration, and evolving industrial paradigms effectively, leading to enhanced organizational outcomes.

As for the final research question, the study findings suggest that construction projects start incorporating C4.0 skills as gaps between different scientific fields grow more interconnected. This has larger implications for the C4.0 concept. The concept provides a novel element to construction projects and reshapes the notion of construction. Despite the conventional perception of construction projects as unproductive, the findings suggest that C4.0 skills are potentially altering this perception, and this transformation is expected to gain momentum soon. Hence, future research should explore the relationship between C4.0 skills and construction project performance. Additionally, considering variables such as training and skill levels as moderators or mediators in this relationship could significantly enhance construction project performance and facilitate the adoption of C4.0.

Lastly, understanding the significance of C4.0 skills is advantageous for skill development and positioning construction projects at the forefront of technological progress and competitiveness. Construction professionals can enhance customer satisfaction, advance sustainability objectives, and stay abreast of technological advancements by adopting these skills, including accurate cost estimations, and streamlined project schedules. Hence, it is critical to establish a link between project execution and C4.0 skills. This relationship is of utmost importance in completely capitalizing on the advantages of C4.0 and ensuring the continuous progress of construction projects.

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