

Systematic Review

Advancing Sustainable Industrialisation in the AEC Sector: A Systematic Review of MMC, Lean Management, Circular Economy and Socio-Digital Enablers

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Abstract

The Architecture, Engineering and Construction (AEC) industry plays a crucial role in global economic development, but it is also a major contributor to environmental degradation and resource consumption. Despite increasing alignment with the United Nations Sustainable Development Goals (SDGs), the sector remains highly fragmented, with limited integration of Modern Methods of Construction (MMC), Lean Management, Circular Economy and Socio-Digital Enablers frameworks into a unified sustainability model. This review article employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to systematically identify and analyse existing literature and address these research gaps. The PRISMA procedure was conducted through a structured process involving the identification of studies from Scopus and Web of Science databases using predefined keywords related to SDGs and the AEC sector. It was followed by screening and eligibility assessment based on publication type, timeframe (2022–2026), subject relevance, and full-text accessibility, resulting in a final dataset of 42 studies for analysis and then applying bibliometric analysis (Biblioshiny and VOSviewer) to define thematic clusters. The results reveal strong research concentration on SDG 11, SDG 12, and SDG 9, while SDG 2 and SDG 14 remain underexplored within the AEC literature. The findings also highlight that the convergence of MMC, Lean Management, Circular Economy practices, and social and digital technologies increasingly drives sustainable industrialisation. A structured content analysis is further conducted to categorise approaches, barriers, and implementation strategies across the four identified components of industrialisation. Overall, this study contributes a comprehensive and integrated framework for understanding sustainable industrialisation in the AEC sector and provides a structured evidence base to support future research and policy development aligned with the SDGs.



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Keywords: sustainable industrialisation; MMC; lean management; circular economy; socio-digital enablers

1. Introduction

Over the decades, the Architecture, Engineering and Construction (AEC) industry has been seen as one of the most important components that contribute to a country's

economic growth. However, it could also be seen as a significant negative impact on environmental sustainability. Due to these effects, a set of global Sustainable Development Goals (SDGs) was proposed by the United Nations General Assembly (Leaders from 193 countries of the world), proposed at the UN in New York, which consisted of 17 different goals and 169 targets. Moreover, a preliminary set of 330 indicators was introduced in March 2015 [1]. Several environmental, economic, and social development concerns, such as health and well-being, poverty, hunger, quality education, gender equality, climate action, water, sanitation, energy, environment, and social justice, have been covered by the UN 2030 Agenda [2]. However, the SDGs have become a challenge for all countries as achieving these goals and targets requires establishing an advanced and well-designed system, thereby increasing the demand for technology, innovation, and resources to build it [3]. To achieve these objectives, the shift toward sustainable industrialisation is no longer optional but essential. This transition relies on a fundamental connection between the physical built environment and innovative digital systems, yet it is hindered by fragmented digital ecosystems and inefficient traditional workflows [4].

Currently, although a growing body of literature explores various solutions to sustainability challenges within the AEC sector, the research scope remains deeply fragmented. Existing studies only focus on investigating the core components of the transformation, such as Modern Methods of Construction (MMC), Lean Management, Circular Economy, Social and Digital Enablers, but in a separate way. The fundamental research gap lies in the fact that implementing these frameworks in isolation frequently generates contradictory sustainability outcomes, creating systemic trade-offs. For example, implementing MMC to accelerate construction efficiency often increases the carbon footprint of transportation logistics if it is not strategically coupled with localised CE materials. The aggressive deploying of digitalised, high-tech manufacturing inherently risks making the AEC's sector vulnerable, along with an informal artisan labour force, unless it is strictly managed by inclusive social and governance frameworks. Consequently, there is a critical lack of a synthesised understanding regarding how these diverse operational and Socio-Digital Enablers interconnect at a system level. To successfully operationalise the UN SDGs, it is no longer sufficient to analyse these elements independently. It is imperative to explore the complex mechanisms of how physical construction methodologies interact with process management strategies, circular material flows, data-driven ecosystems, and localised governance frameworks. Furthermore, there is an urgent need to define the systemic barriers and operational trade-offs that prevent their unified application across the lifecycle.

To address this critical research gap, this study conducts a comprehensive systematic literature review designed to transcend these isolated research domains. The objective is to establish a holistic context for sustainable industrialisation by investigating the systemic interdependencies between components among the AEC sector's core transitional components. By systematically mapping current research trends, this review analyses the critical synergies between physical operations, materials innovations, and Socio-Digital Enablers. Ultimately, by analysing both technical, social, and economic bottlenecks, this study proposes a strategic, integrated roadmap to guide policymakers and industry stakeholders in navigating the complex transition to achieve sustainable and equitable industrialisation.

2. Methods

A systematic literature review of previous research is a widely used method to identify and evaluate a specific topic, comprehend relevant published articles, and also provide a valid summary of the available articles [5]. It was selected as the foundational methodology for this study to completely evaluate, synthesise, and structure the fragmented academic discourse surrounding the AEC sector's transition. The primary objective of this study is to establish a comprehensive framework for sustainable industrialisation by identifying how diverse operational, management strategies, materials, social, and technological components interconnect. The scope of this review is focused explicitly on recent academic literature that investigates the implementation of components towards sustainable industrialisation transition. The 42 selected papers deliberately explored different domains, ranging from quantitative laboratory tests on the structural properties of materials to qualitative social and economic case studies evaluating artisan labour policies or some governance policies. Because the dataset also included incommensurable variables, a qualitative thematic synthesis was selected as the most appropriate approach to accurately map the multi-dimensional interaction and systemic trade-offs between MMC, Lean Management, Circular Economy and Socio-Digital Enablers across the AEC sector.

This article explores which components should be integrated in the framework to develop sustainable industrialisation in the AEC sector; how they support each other and addresses key research questions, such as which tools, technologies, and management processes have been applied; how they have been implemented; and their impacts on SDGs. To select the study sample and assess each article's relevance, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA 2020) methodology was developed. The PRISMA 2020 checklist is provided in the Supplementary Materials. The article extraction process comprises three stages: (i) Identification, (ii) Screening, Filtering, and Eligibility, and (iii) Inclusion.

2.1. Stage I: Identification

The initial search was performed by using the Scopus and Web of Science (WoS) databases to ensure their complementary scopes and high relevance to systematic review. The primary search combined keywords including 'SDGs', 'Sustainability Development Goals', 'construction' and 'construction sector' to capture a broad range of literature at the intersection of global sustainability and industry practices in AEC.

Although the concepts of these main components have decades of history, this study restricts its scope to 2022–2026 to capture a critical paradigm shift in the AEC sector. While earlier literature mainly focused on these drivers in theoretical silos, the time after 2021 saw the remarkable convergence with modern digital enablers, such as Artificial Intelligence and Enhanced Digital Twins. Furthermore, the urgency of the UN 2030 Agenda has fundamentally shifted research away from isolated efficiency metrics and toward integrated, SDG-driven governance frameworks.

2.2. Stage II: Screening, Filtering, and Eligibility

The results were refined using filtering steps based on timeframe, types of articles, subject areas, and journals criteria:

- Timeframe: The selected articles were filtered to include the publications from 2022 to 2026 to ensure the review reflects the most current post-COVID-19 research and the latest advancements toward the 2030 Agenda.
- Types of articles: Conference, review, and research article.

- Subject areas: The search was limited to specific domains such as Architecture, Engineering, and Construction.
- Journal: Several journal articles included.

To ensure the high relevance of the synthesised literature, a strict set of inclusion and exclusion criteria was established. The primary filtering criterion restricted the dataset strictly to peer-reviewed journal articles and comprehensive review papers, and high-impact conference proceedings. By including these specific documents types, this study ensures that the selected data is of high academic quality while also capturing the most recent technological advancements.

After the initial filtering process, a multiple-stage qualitative assessment was conducted. First, each record was screened by reading its title and abstract to determine its suitability for the core topic of sustainable industrialisation, and the articles deemed irrelevant to the study were excluded. Articles were sought that specifically addressed MMC, Lean Management, and the use of Circular Economy, and social and governance aspects that link to sustainable industrialisation. Following the initial screening phase, a full-text eligibility assessment was conducted to refine the dataset. Articles were excluded from the final selection if full-text access was unavailable.

Furthermore, to ensure strict alignment with research objectives, a rigorous set of exclusion criteria was applied. First, articles were removed if they failed to align research outcomes directly with the targeted UN Sustainable Development Goals (SDGs). Because the term ‘sustainability’ is often used as a generic term in AEC literature, recently studies have lacked targeted SDG metrics that could not be systematically analysed for specific environmental outcomes. Studies that did not explicitly align with the SDGs were deliberately excluded in this study to keep analysis focused on the whole concept. While there is plenty of valuable research covering indirect environmental benefits, this study’s goal was investigate how technical advancements intersect with social equity and macro-level governance. By applying this filter, the dataset directly addresses the complex policy and socio-economic trade-offs required for sustainable industrialisation. Second, studies were excluded if they focused on traditional tools and techniques because this article investigated the paradigm shift toward industrialisation and modern improvements to conventional, fragmented site-based methods. Finally, articles lacking a clear operational management plan or implementation framework, such as purely theoretical models, were deemed ineligible. To properly investigate systemic integration, management plan, and strategic governance, the selected articles had to demonstrate how these tools are actively deployed within the realities of the AEC project lifecycle.

2.3. Stage III: Inclusion

Following the eligibility assessment, a final set of 42 articles was selected for the full-text reading and qualitative synthesis. These articles represent the core evidence base for answering the research questions regarding the convergence of MMC, Lean Management, Circular Economy and Socio-Digital Enablers in the modern AEC industry. Additional methodological details, including the complete search strategies, are provided in the Supplementary Materials. Details about the different steps are summarised in Figure 1.

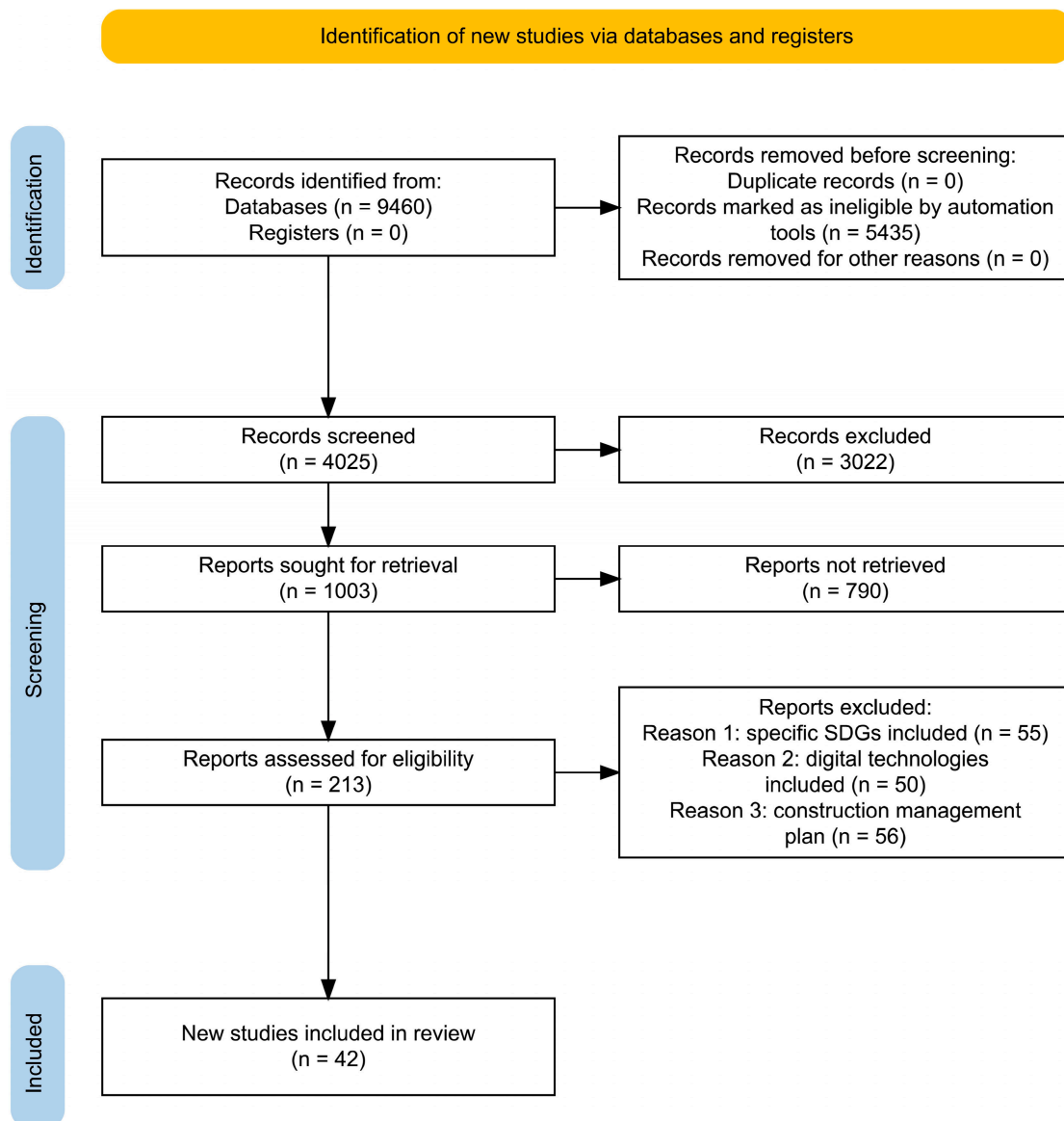


Figure 1. An overview of the PRISMA methodology for the literature search strategy [6].

After these three stages, to select the relevant articles reviewed in this article, bibliometric mapping was performed. The metadata, including year, authors, journal, country and keywords, were imported into Biblioshiny (R-package) and VOSviewer [7]. These tools enabled visualisation of co-authorship networks, keyword co-occurrence and thematic clusters.

For the qualitative phase, a deductive content analysis was conducted on the final set of 42 articles. A structured analysis was designed with three analytical dimensions: approaches, barriers and application methods. The objective of this initial analysis was to identify the dominant clusters of research currently driving the transition within the AEC sector.

2.4. Research Questions

The result revealed four distinct enablers that could be seen in Section 1, all of them highly interconnected thematic clusters required for industry transformation, including Modern Methods of Construction and Lean Management, Circular Economy, and Socio-Digital Enablers.

It became evident that while the literature thoroughly investigates these areas individually, the ultimate challenge lies in their integration. Consequently, to systematically

investigate these data-driven themes and address the overarching research gap regarding industry-wide integration, the primary aim of this review was operationalised into specific research questions below. These research questions were designed to explore the synergistic and trade-off relationships inherent in sustainable industrialisation, specifically spanning physical construction processes, circular materials, data-driven technologies, and localised policy frameworks. Ultimately, by structuring this inquiry around three analytical levels, including core components, integration mechanisms and SDG sustainability outcomes, this review will provide a comprehensive framework for the AEC sector's transition.

- RQ1: How are the core components of sustainable industrialisation (MMC, Lean, Circular Economy, and Socio-Digital) implemented across the different phases of the AEC project lifecycle?
- RQ2: What operational synergies and trade-offs emerge when integrating these diverse components?
- RQ3: How can stakeholder engagement and localised governance frameworks resolve the systemic barriers hindering sustainable industrialisation?

3. Bibliometric Analysis

As shown in Table 1, a marked increase in publication volume can be seen from 2022 onward. The annual growth rate of publication reached 53.14%, with 2025 recording the highest number of contributors ($n = 18$). Furthermore, Table 2 shows the journals of 42 reviewed articles that were selected in this study, with the top sources including Ecological Indicators (four articles), followed by Journal of Building Engineering, Journal of Cleaner Production, International Journal of Building Pathology and Adaption and Sustainable Futures, reflecting a multidisciplinary engagement with sustainability and architecture, engineering and construction themes.

Table 1. Overview of the bibliometric dataset (2022–2026) used in this systematic review, summarising time span, core sources, document counts, authors and citation statistics.

Main Information About Data ¹	
Timespan	2022:2026
Sources (journals, books, etc.)	31
Documents	42
Annual growth rate %	53.14
Document average age	1.26
Average citations per doc	29.9
References	3529
Document Contents ¹	
Keywords plus (ID)	362
Author's keywords (DE)	176
Authors ¹	
Authors	42
Authors of single-authored docs	42
Authors Collaboration ¹	
Single-authored docs	42
Co-Authors per Doc	1
International co-authorships %	38.1

Table 1. *Cont.*

Document Types ¹	
Article	31
Review	10
Conference article	1

¹ Data source/Method used: Scopus and Web of Science/Biblioshiny (R) 4.1.2.

Table 2. List of journals of selected articles.

Sources ¹	Articles
Ecological Indicators	4
Journal Of Building Engineering	3
Journal Of Cleaner Production	3
Energy And Buildings	2
Environmental Impact Assessment Review	2
International Journal Of Building Pathology And Adaptation	2
Sustainable Futures	2
Alexandria Engineering Journal	1
Buildings	1
Built Environment Project And Asset Management	1
Cleaner Environmental Systems	1
Cleaner Waste Systems	1
Construction And Building Materials	1
Construction Innovation	1
E3S Web Of Conferences	1
Energies	1
Innovative Infrastructure Solution	1
International Journal Of Lean Six Sigma	1
Journal Of Building Pathology And Rehabilitation	1
Journal Of Construction In Developing Countries	1
Journal Of Environmental Management	1
Land Use Policy	1
Management And Sustainability	1
Remote Sensing Of Environment	1
Research In Globalization	1
Reviews On Advanced Materials Science	1
Sustainable Chemistry One World	1
Sustainable Cities And Society	1
Sustainable Development	1
Sustainable Production And Consumption	1
World Development Sustainability	1

¹ Data source/Method used: Scopus and Web of Science/Biblioshiny (R) 4.1.2.

3.1. Country Contribution Mapping

The geographical distribution of research contributions highlights a global engagement with sustainable industrialisation in the AEC sector (Figure 2). Some countries, such as China ($n = 28$), Australia ($n = 13$) and India ($n = 10$), emerge as the most influential and prolific contributors to sustainability and digital industrialisation research. It is important to clarify, however, that this distribution reflects academic output and institutional research rather than the actual extent of comprehensive SDG implementation within these nations' industries. Therefore, while these studies indicate the substantial volume of scholarly attention and technological investment in this topic, they should not be construed as evidence of real-world transitions away from conventional construction practices towards the new methods that are recommended in this research.

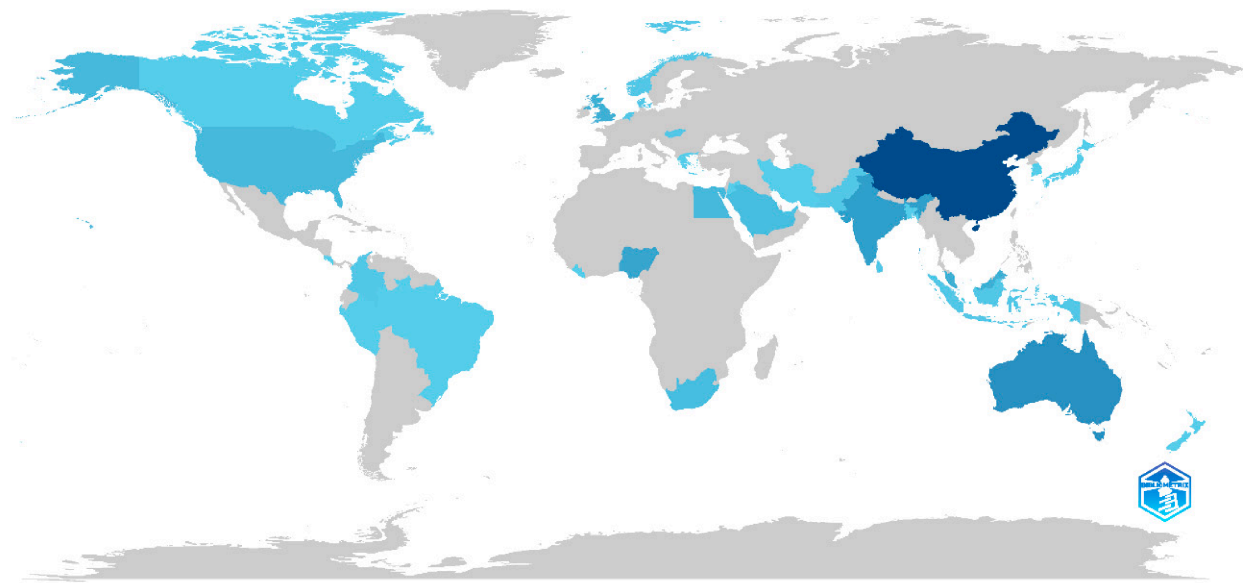


Figure 2. Countries' contribution map for the 42 reviewed articles, highlighting leading contributors and regional coverage. (Data source/Method used: Scopus and Web of Science/Biblioshiny (R) 4.1.2).

Nevertheless, examining the contextual strengths and strategic initiatives of the represented countries offers valuable insights into each country's broader sustainability efforts. China, for example, has illustrated a strong commitment to policy localisation by actively integrating SDGs into its national ecological civilisation construction strategy and utilising advanced geospatial data fusion technologies to map urban construction sites at the national scale. In another effort, Denmark demonstrates leadership in practical and project-level applications, focusing on the early stages of integration of multiple goals of sustainable development (particularly SDG 4—Quality Education, SDG 9—Industry, Innovation and Infrastructure, SDG 12—Responsible Consumption and Production, and SDG 13—Climate Action) into public infrastructure development [8]. Additionally, Australia and India offer various valuable regional perspectives. Particularly, Australia is actively assessing stakeholder viewpoints to address barriers to sustainable prefabricated construction [9], while India has been focused on infrastructure evaluation and on addressing the systemic challenges in achieving SDG 6—Clean water and Sanitation [10].

Crucially, the included dataset also features contributions from emerging and developing economy countries, addressing a recognised gap in the literature from low- and middle-income nations. Research in other countries underscores the innovations and localised approaches to the application of Circular Economy, such as the incorporation

of industrial residues (RFCC) into lightweight concrete and the repurposing of plastic waste into viable alternative materials [11], or the urgent necessity of improving personal protective equipment (PPE) awareness in construction sites and access to health insurance among informal sector artisans [12]. The inclusion of these regions signifies an expanding and growing global interest in SDG-related AEC research and highlights opportunities for improving sustainability and industrialised practices to solve specific challenges in developing countries.

3.2. Network Visualisation

To comprehend the complex research landscape of sustainable industrialisation within the AEC sector, this study employs bibliometric network visualisation. This approach builds upon the conceptual foundations of Social Network Analysis, which examines the importance of relationships among interacting units [13]. From this perspective, social networks encompass theories, models, and applications that are shown in terms of relational concepts and processes. Relations, defined by the linkages among units, are a fundamental component of network theories. This methodology examines the relationship among various research entities by representing them as an interconnected web. Within this framework, each analytical unit, such as a specific keyword or an author, can be represented as a node, while co-occurrence or citation relationships between them are represented as connecting edges. By analysing network metrics like link strength, proximity and clustering, this approach effectively reveals the underlying thematic associations and community structures driving the field's advancement toward the SDGs [14].

In these visual representations, the physical characteristics of the network provide immediate insights into the literature's priorities. The size of a node correlates directly with its frequency of occurrence. For example, in co-occurrence analysis, prominent keywords, such as 'Modern Construction' or 'Circular Economy', appear as larger nodes due to their high prevalence within the selected topic. Furthermore, the spatial proximity between each node signifies the strength of the relationship, with shorter distances indicating that concepts are frequently investigated [15]. The thickness of the connecting links further quantifies this association, reflecting the absolute number of documents or citations linking the two entities.

To systematically map the convergence of MMC, Lean Management, Circular Economy, and Digital Enablers, this study aimed to construct two distinct types of networks. First of all, a keyword co-occurrence analysis was utilised to determine how often specific keywords appear together, which helps group the research into primary thematic clusters and illustrates how technological innovations intersect with specific environmental goals. Secondly, an author co-citation analysis was performed to map the intellectual structure of the discipline, highlighting the number of sources in which two authors are cited together. These networks were developed in VOSviewer based on bibliometric data to reveal thematic clusters, consensus within the field, and the structure of scholarly collaborations [16].

3.2.1. Keyword Dynamics

To ensure data accuracy, a standard data cleaning process was initially applied to consolidate terms with identical or closely related meanings. Keywords were retained for analysis and used to construct the network co-occurrence map shown in Figure 3.

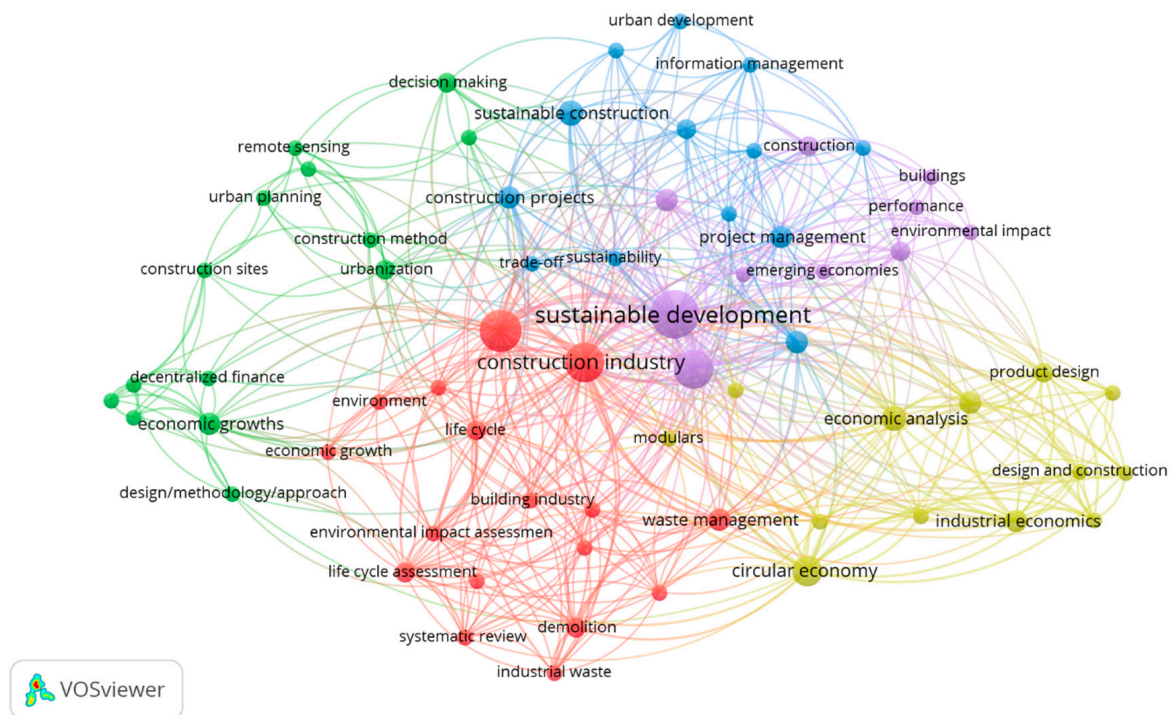


Figure 3. Keyword co-occurrence network showing thematic clusters and relationships among key terms within the SDG literature. Tool: VOSviewer (v.1.6.20). Items: 67. Clusters: five. Links: 561. Total link strength: 764.

The visual analysis identified five principal thematic clusters that provide a complete view of the evolutionary stages of sustainable industrialisation identified in this review:

- Cluster 1 (Purple) is anchored by the prominent node 'sustainable development' that shows the main theme of this review. It included terms defining strategic oversight and global contexts, including 'project management', 'buildings', 'emerging economies', 'buildings', and 'environmental impact'.
- Cluster 2 (Red) is centred on the 'construction industry' node; this cluster highlights the industry's significant shift toward long-term environmental accountability and end-of-life considerations. This cluster groups interconnected terms reflecting environmental impact and assessment, such as 'life cycle', 'environment', 'waste management', and 'demolition'.
- Cluster 3 (Yellow) highlights the transition toward resource efficiency and economic sustainability. This cluster focused on the financial and practical frameworks required for close-loop systems, connecting the prominent node 'circular economy' with related systemic concepts like 'industrial economics', 'economic analysis', 'design and construction', and 'product design'.
- Cluster 4 (Green) emphasises the social and economic framework and spatial dynamics of sustainability. It connects broader systemic concepts like 'economic growth' with spatial execution terms such as 'urban planning', 'urbanisations' and alternative funding models like 'decentralised finance'.
- Cluster 5 (Blue) showcases the integration of modern execution and data processes. This cluster demonstrates the operationalisation of sustainability in active environments, grouping 'sustainability', 'sustainable construction', and 'construction projects' with forward-looking support systems like 'information management' and 'urban development'.

Further analysis of the network reveals that ‘sustainable development goals’, ‘sustainability’ and ‘circular economy’ act as the primary intellectual hubs, characterised by the largest node sizes and the highest density of connecting links. As expected, their strong co-occurrence reflects the overarching scope of this study. Nevertheless, the emergence of five clusters indicates a significant evolution in the AEC sector. The literature has clearly progressed from a generalised awareness of sustainable industrialisation toward a highly fragmented, deeply technical exploration of specific implementation pathways in construction methods, circular resources and digital enablers, and social equity.

3.2.2. Co-Citation and Author Influence

In the co-citation analysis, which uses cited authors as the unit of measurement, a total of 8222 cited authors were identified across the 42 reviewed articles. Among these authors, only 58 met the threshold of receiving at least 10 citations. The network visualisation can be seen in Figure 4.

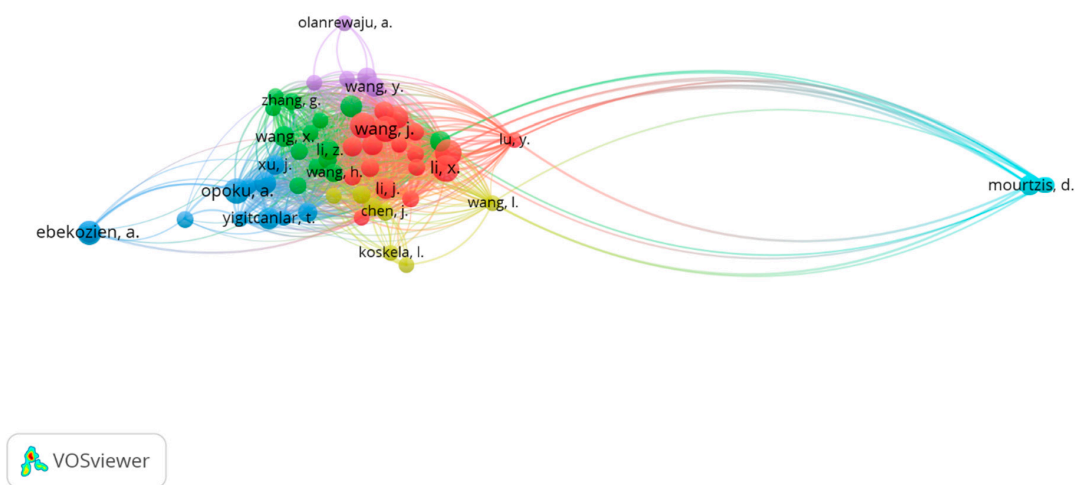


Figure 4. Author co-citation network highlighting the key scholars from reviewed articles in SDGs and sustainable industrialisation. Tool: VOSviewer (v.1.6.20). Items: 45. Clusters: six. Links: 796. Total link strength: 8048.

This citation pattern reveals a highly fragmented research landscape. While the network demonstrates strong internal linkages within specific subfields that indicate established research in isolated sectors, such as physical construction methods, or material circularity, there is a distinct lack of cross-disciplinary citation. It underscores the field’s foundational reliance on isolated theoretical frameworks rather than a consolidated, integrated body of empirical research. Specifically, the data show a critical gap in knowledge transfer between operational management strategies such as construction methods, Lean Management, circularity, social, governance enablers, and specific SDG implementation. Consequently, there is an urgent need to increase the cluster’s scholarly engagement. Future empirical publications and collaborative research must bridge this gap to build a unified, realistic knowledge base for sustainable industrialisation.

3.2.3. Reflection on Limitations

Bibliometric analysis is valuable for identifying patterns in the reviewed articles and for assessing academic attention to a specific topic; however, it presents several limitations. It cannot measure the actual applications or impacts of each component of the strategies included in the study, and trends are sensitive to keyword, database coverage or language bias. Therefore, findings from this section provide context for the deeper qualitative insights developed in Section 4 (Result Analysis).

4. Result Analysis

This section presents a qualitative analysis of the 42 selected articles relevant to the main topic, focusing on the four components mentioned in Section 2 (Research Methodology): (i) Modern Methods of Construction, (ii) Lean Management, (iii) Circular Economy, (iv) Socio-Digital Enablers. This section also aims to respond to the research questions of the study and provides some recommendations for the implementation of achieving SDGs through sustainable industrialisation.

4.1. Sustainable Development Goals

Given the growing importance of sustainability across sectors, particularly in Architecture, Engineering and Construction, the introduction of the SDGs by the United Nations should be recognised. The SDGs serve as a worldwide framework aimed at eliminating poverty, safeguarding the environment and promoting prosperity for all, as outlined in the 2030 Agenda [17]. According to [18], sustainable development is broadly divided into three interconnected dimensions: economic, environmental and social sustainability. Among these three pillars, economic sustainability emphasises long-term stability and the efficiency of resources used in the construction projects, and environmental sustainability focuses on natural preservation and ecological harm reduction. On the other hand, social sustainability addresses well-being, equity and justice for current and future generations. To achieve the SDGs comprehensively, all stakeholders should integrate the proposed four components of sustainable industrialisation into the three pillars. Table 3 shows the objectives of each of the 17 SDGs specifically tailored to the AEC sector, and the classification into three dimensions of sustainability: economic, environmental, and social.

Table 3. The 17 SDGs and their objectives in the AEC sector.

No	SDG	Pillars Classification	Objectives	Refs.
SDG 1	No Poverty	Economic	- Design and construct low-cost, resilient housing and essential infrastructures - By physically connecting communities to basic services, this enables economic mobility	[19]
SDG 2	Zero Hunger	Economic Social	- Develop the physical infrastructure required to support sustainable agriculture and food security (such as controlled climate storage facilities and transportation networks that prevent food loss between farms and urban centres)	[19]
SDG 3	Good Health and Well-being	Social	- Build space that actively promotes human well-being (such as designing modern healthcare facilities, nursing homes)	[19]
SDG 4	Quality Education	Social	- Construct safe, accessible and inclusive educational facilities - Interactive training for employees, staff, and upskilling workers in green practices and modern technologies - Promoting continuous learning in the engineering and design phase of projects	[20,21]
SDG 5	Gender Equality	Social	- Institutionalising gender policies, increasing female representation in leadership and other positions, ensuring an equitable, safe and inclusive working environment across the construction sector	[22,23]

Table 3. Cont.

No	SDG	Pillars Classification	Objectives	Refs.
SDG 6	Clean Water and Sanitation	Environmental	- Create an eco-friendly society with clean water resources and a sanitation system	[24]
SDG 7	Affordable and Clean Energy	Economic	- Transition the built environment away from fossil fuels - Design highly efficient-energy or net-zero buildings and construction of the physical infrastructure for renewable energy	[25]
SDG 8	Decent Work and Economic Growth	Economic	- Promote fair, safe and transparent working environments by improving labour conditions, enforcing ethical business practices (anti-corruption and anti-competitive measures) - Enhance corporate transparency and strengthen governance across the construction sector	[26,27]
SDG 9	Industry, Innovation and Infrastructure	Economic Social	- Align with corporate policies and environmental challenges, which drive innovation and sustainable industrial practices - Promote corporate social responsibilities, and strengthen sustainable relationships with suppliers and clients across the value chain	[28,29]
SDG 10	Reduced Inequalities	Social	- Promote equitable urban planning that bridges the gap between different socio-economic groups	[24]
SDG 11	Sustainable Cities and Communities	Economic Environmental	- Support sustainable urban development by fostering community development initiatives - Advance the development of green housing through environmentally responsive design and planning	[21,30]
SDG 12	Responsible Consumption and Production	Economic Environmental	- Minimise environmental impacts by managing emissions and waste that are released while promoting the efficient use of resources and materials - Adhere to sustainability standards and procedures throughout the construction lifecycle	[27]
SDG 13	Climate Action	Environmental	- Reduce the overall environmental footprint of the projects by lowering greenhouse gas emissions, optimising building performance and enhancing climate resilience	[31]
SDG 14	Life Below Water	Environmental	- Protect marine ecosystems by strictly managing construction site runoff, preventing microplastics and chemicals from entering waterways	[24]
SDG 15	Life on Land	Environmental	- Minimise the ecological footprint of construction projects (such as avoiding deforestation)	[24]
SDG 16	Peace, Justice and Strong Institutions	Social	- Promote transparent procurement processes, ethical supply chains, and collaborative community planning	[24]
SDG 17	Partnerships for the Goals	Social	- Strengthen collaboration with environmental agencies and conservation organisations to support knowledge sharing - Implement sustainable development practices at a large-scale	[30]

4.2. Sustainable Development Goals Included

An analysis of the 42 selected articles reveals a diverse alignment across the 17 Sustainable Development Goals (SDGs), with the details comprehensively mapped in Table 4. It can be seen from the table that the most frequently addressed SDG is SDG 11 with 30 instances across 42 reviewed articles, followed by SDG 12 ($n = 27$) and SDG 9 ($n = 26$). In comparison, SDG 2 and SDG 14 (both with $n = 7$) appear to be the least represented in the AEC sector.

Table 4. SDGs included in the reviewed article.

No	References	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
1	[32]												x					
2	[33]													x				
3	[12]			x														
4	[34]						x	x	x	x	x	x	x	x		x	x	x
5	[35]			x														
6	[36]								x	x			x					
7	[37]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8	[38]			x				x	x	x		x	x	x		x		x
9	[39]									x		x	x					
10	[40]						x	x	x	x		x	x	x		x		x
11	[41]									x		x	x	x				
12	[42]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
13	[8]				x					x			x	x				
14	[43]									x								
15	[44]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
16	[45]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
17	[46]	x		x	x				x	x		x						
18	[47]			x					x				x	x	x			
19	[11]											x		x				
20	[48]											x						
21	[49]						x					x	x					
22	[9]			x		x	x	x	x	x		x	x	x		x		
23	[10]						x											
24	[24]	x		x	x		x	x	x	x	x	x				x		
25	[50]											x						
26	[51]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
27	[52]									x		x	x					
28	[53]											x	x					
29	[54]								x	x		x	x					
30	[19]	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	

Table 4. *Cont.*

No	References	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
31	[55]									x		x						
32	[56]									x			x			x		
33	[57]						x	x	x			x		x				
34	[58]	x	x		x	x				x	x	x	x	x			x	
35	[59]			x	x		x	x	x	x	x	x	x				x	
36	[60]											x						
37	[61]							x				x		x				
38	[62]									x		x						
39	[63]									x		x	x					
40	[64]											x	x	x				
41	[65]									x			x					
42	[66]				x	x			x		x		x	x			x	

4.3. Four Main Components of Sustainable Industrialisation

With the advanced development of technologies, the integration of construction methods, Lean Management, circularity, and Socio-Digital Enablers can be seen clearly in the achievement of sustainability. To systematically evaluate the literature, the 42 selected articles were categorised into four distinct components of sustainable industrialisation. The literature review focused on the four components of sustainable industrialisation and required an integrated and systemic approach rather than isolated interventions. Their combined implementation forms a comprehensive framework for achieving the objectives of the UN 2030 Agenda. As detailed in Table 5, this classification not only identifies the primary focus of each study but also highlights the critical intersections where (S1): MMC; (S2): Lean Management; (S3): Circular economy and (S4): Socio-Digital Enablers integrate.

Table 5. Specific components in each reviewed article.

No	References	Stages	No	References	Stages
1	[32]	(S4)	22	[9]	(S1)
2	[33]	(S4)	23	[10]	(S3)
3	[12]	(S4)	24	[24]	(S4)
4	[34]	(S4)	25	[50]	(S4)
5	[35]	(S4)	26	[51]	(S1)(S3)
6	[36]	(S1)(S2)	27	[52]	(S1)(S3)
7	[37]	(S4)	28	[53]	(S2)
8	[38]	(S4)	29	[54]	(S2)
9	[39]	(S1)	30	[19]	(S4)
10	[40]	(S4)	31	[55]	(S1)(S4)
11	[41]	(S4)	32	[56]	(S3)

Table 5. *Cont.*

No	References	Stages	No	References	Stages
12	[42]	(S4)	33	[57]	(S2)
13	[8]	(S2)	34	[58]	(S4)
14	[43]	(S4)	35	[59]	(S3)
15	[44]	(S3)(S4)	36	[60]	(S4)
16	[45]	(S4)	37	[61]	(S3)
17	[46]	(S4)	38	[62]	(S3)
18	[47]	(S3)	39	[63]	(S3)
19	[11]	(S3)	40	[64]	(S3)
20	[48]	(S2)	41	[65]	(S3)
21	[49]	(S3)	42	[66]	(S3)

5. Content Analysis

5.1. The Implementation of Core Components Across Different Phases of the AEC Project Lifecycle

The transition toward sustainable industrialisation requires a fundamental shift in how construction projects are created, executed and dismantled. Thematic analysis from 42 reviewed articles shows four core components, MMC, Lean Management, Circular Economy and Socio-Digital Enablers, are not uniformly applied. In that case, each component is implemented strategically in different phases of the AEC projects' lifecycle, aiming to maximise efficiency and SDG alignment.

5.1.1. MMC: Shifting from On-Site Construction to Off-Site Manufacturing

Modern Methods of Construction (MMC) represents a transformative innovation that outperforms conventional, labour-intensive in situ methods, such as brick-and-block, in speed, quality, and sustainability [67,68]. By transferring up to 90% of construction activities into controlled factory environments instead of on construction sites, MMC allows buildings to be fully defined in the design phase, contributing to highly predictable projects and reducing the need for on-site improvisation [69,70]. Recently, articles in the literature have covered various MMC approaches, including prefabricated concrete and off-site and modular construction, which receive the most attention due to their broad applicability, alongside augmented output and earthquake-resilient beam–column joints [71].

Operationally, off-site manufacturing enables parallel execution between factory production and construction site preparation, contributing to the construction time being shortened and on-site activities being decreased [72–74]. This industrialisation process integrates automation, keeps projects always on schedule, and promotes greater specialisation among stakeholders, yielding higher quality outcomes for construction projects [75]. An example of the rapid delivery of this method is the construction of two emergency hospitals in Wuhan, China, during the COVID-19 pandemic, completed in just 12 days [76].

Crucially, MMC addresses the severe resource consumption and emissions relevant to the conventional construction methods, directly aligned with SDGs by diminishing a building's lifecycle footprint [67,77]. Off-site prefabrication significantly lowers energy consumption, carbon emissions, dust and noise [78,79], and also decreases the material waste by up to 60% [80,81]. Furthermore, transporting assembly into controlled environments actively prevents accidents and mitigates worker exposure to hazardous conditions, creating a significantly safer labour environment [78,80,81].

Modern Methods of Construction, especially prefabricated, modular construction, and precast concrete manufacturing, have changed the conventional construction lifecycle by transferring most of the physical labour from the on-site execution phase to the off-site manufacturing phase [9,52]. However, the thematic analysis reveals that simply moving construction indoors does not automatically achieve sustainability. To successfully industrialise the sector to achieve SDGs, MMC must be structurally and operationally optimised across phases of the project lifecycle. The transition toward sustainable industrialisation should begin at the conceptual stage, from the beginning of a construction project.

Firstly, in the design and pre-construction phase, unlike traditional methods, MMC requires building components or structures to be strictly standardised and completely engineered for factory production. This early-stage coordination allows quantifying material resources exactly and implementing sustainability assessments such as Life Cycle Economic Sustainability (EcS) or Social Sustainability (ScS) before physical manufacturing commences, ensuring that the project is optimised for resource efficiency [39]. By standardising components, material resources can be quantified exactly and intentionally avoid over-specification. It can lead to the advancement of SDG 9 by enhancing productivity and reducing waste, SDG 12 by the reduction of waste released into the environment and energy efficiency, and SDG 11 by the enhanced community engagement and improved worker safety awareness. By applying modern methods and sustainable assessment tools in this phase, Ref. [82] found that the sustainability indicators were higher than those of conventional methods by an average of 21% in social, 52% in environmental, and 60% in economic indicators.

Secondly, in the construction/execution phase, for the conventional construction method, the process only includes the construction activities at the construction site, while modern construction methods include manufacturing activities in the factory off-site and assembly on-site. The core industrialisation process occurs within strictly controlled factory environments. In this step, prefabricated or modular construction follows industrial manufacturing logic, significantly reducing raw material waste compared to traditional on-site pouring [36]. In this phase, the industrial shift could be seen clearly, where building elements are produced with a high level of mechanical precision, leading to the structural quality improvement and lower waste energy through the optimisation of material usage [9]. With the insights from 21 stakeholders from the prefabricated industry, sustainability indicators were divided into three main pillars: environmental, economic and social. Among these, environmental impact was considered as the most important impact, with energy performance and efficiency, waste management, and material consumption in construction as factors that lead to the achievement of SDG 7 and SDG 12, and to structural quality improvement and wasted energy reduction.

Furthermore, shifting labour indoors also provides safer working conditions, supporting SDG 8. In another case, assembly on-site reduced the construction duration and environmental impact, like noise, dust and traffic congestion, directly contributing to SDG 11 (Sustainable Cities and Communities) [51]. However, to achieve sustainable industrialisation in this phase of the project, it is required to have a sophisticated system; the benefits of off-site manufacturing need to align with the carbon footprint (SDG 3 and SDG 6) and logistical complexity of transporting large-scale modular components to the construction site [9].

Finally, in the end-of-life phase, MMC plays an important role in supporting long-term sustainability by the inherent modularity of its components. Because each element is produced separately as a discrete unit, in this phase, it is easier to dismantle and reuse at the end of the building's lifecycle. This structural flexibility ensures that industrialisation

does not lead to permanent waste but will create available material resources for future construction cycles [51,52].

5.1.2. Lean Management

In the context of the AEC industry's transition toward sustainable industrialisation, lean manufacturing can be seen as a vital operational framework to optimise the use of MMC and ensure process efficiency. Ref. [83] defined 'lean' as an approach to designing a production system that can minimise waste of materials, time, labour efforts, and resources, while maximising value. Since the mid-1990s, lean construction has emerged as a concept in both management theory and practice. It can be understood either as the application of lean production techniques to construction or as a theory-based approach inspired by lean principles. Lean construction management can be regarded as an advanced industrial management model that focuses on reducing disruptions and variability in site operations by controlling the duration of each construction activity and the scale of work, aimed at achieving a continuous workflow across project stages [84]. This approach enhances the operational flexibility of projects through the implementation of standardised processes and the selection of suitable controlled production methods [85].

Furthermore, LCM is highly compatible with the transition toward MMC, particularly in prefabricated building projects, as both approaches share the same goals of waste minimisation and process standardisation [86]. In practice, the integration of different lean techniques within industrialised workflows offers several benefits:

- Process Optimisation tools: Value-Stream Mapping (VSM) and Just-In-Time (JIT) application allow for the continuous monitoring and improvement of manufacturing networks [87]
- Performance Enhancement: Implementing lean strategies in precast and modular projects significantly elevates product quality and construction technologies [85]
- SDG Alignment: By eliminating non-value-added activities and reducing emissions released, lean practices directly contribute to the achievement of SDG 8, SDG 9, SDG 11 and SDG 12, etc. [54]

With the lean implementation executed from the beginning phase of the lifecycle, during the design and planning step, project teams started using tools like Value Stream Mapping to visualise the entire production flow, from the raw material delivery to product deliveries [53]. From this approach, this article defined five terms for lean strategies, like lean for sustainable development, lean for workflow improvement, lean for waste elimination, lean for optimising delivery, and lean with digital technologies, to reduce waste, increase value for clients, and lower emissions. From those, the approach can achieve SDG 8, SDG 9, and SDG 12 [53,54].

This early-stage implementation is critical for establishing standardised industrialisation processes. By mapping workflow before the physical execution stage, Lean Management allowed teams to define and eliminate non-value-adding activities and address the inherent inefficiencies in resources [54]. This strategy promotes resource efficiency and reduces the environmental footprint of construction activities, which contribute to SDG 12.

When the project moves into the construction/execution phase, lean is applied to manage the physical flow of material sources. Within industry or factory settings, such as precast concrete manufacturing, lean is operationalised through the Just-In-Time system by scheduling the delivery of materials exactly when they are needed for manufacturing, helping minimise material waste, reduce project overlays, and lower overall cost, thus supporting the development of sustainable infrastructure and resilient communities (SDG 9, SDG 11) [36]. Supply chain collaboration and coordination would define the successful implementation at this stage in the lifecycle. By stabilising workflow and ensuring material

is transported on time, lean minimises on-site variability, focuses on circularity, innovates, reduces redundancy and fosters a reliable, highly cooperative working environment (SDG 4, SDG 9, SDG 12, SDG 13) [8].

Lean also needs to be implemented as a long-term operational strategy to achieve sustainable industrialisation. In some cases, lean should be integrated directly into the business model of the AEC sector, aimed to not only support global sustainability objectives but also bring some positive impacts to long-term business performance, enhanced reputation, market differentiation, and improved stakeholder relations (SDG 5, SDG 7, SDG 9, SDG 10, SDG 13) [57]. Furthermore, logical lean, especially the elimination of fragmented and disconnected workflows, is applied to large-scale urban renewal, actively contributing to spatial and ecological waste, supporting SDG 11 to ensure universal access to safe, inclusive green spaces [48].

5.1.3. Circular Economy

However, industrialisation alone is insufficient without a transition to the Circular Economy. Circular principles focus on closing, slowing, narrowing and regenerating resource loops across both technological and biological systems, prioritising the upcycling or direct reuse of building components instead of downcycling them through conventional recycling [88–91]. By implementing better waste recycling practices, end-of-life plastics can be converted from being disposable and reintegrated into sustainable products, leading to improved recovery and reuse of recycled materials [92]. The industry is increasingly exploring the application of construction and demolition (C&D) waste to minimise environmental impacts and conserve natural resources [93]. This circular approach not only addresses the critical issue of waste disposal but also supports the achievement of several SDGs, including SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [11,44,46,47].

The term ‘Circular Economy’ emerged in the 1980s, originally from two related ideas: a closed-loop economy and the concept of designing for redesign. The pillars of the Circular Economy align with the three dimensions of sustainability: social, economic and environmental [94]. According to [95], a Circular Economy can be understood as an economic system that replaces the traditional ‘end-of-life’ concept with strategies to reduce, reuse, recycle, and recover material throughout the production, distribution, and consumption processes. In contrast, the linear economy follows a ‘take–make–dispose’ approach [96]. Especially in the context of industrial waste management, applying Circular Economy principles is essential for converting construction waste into valuable resources for the next construction projects [96]. Sustainable material innovation involves both technical approaches, like replacing materials and reducing their usage, and non-technical strategies that include the development of new business models grounded in lifecycle aspects such as dematerialisation and closed-loop systems [97]. Some material innovations applied in the construction sector, as reported in [98], include 3D printed sandstone, aluminium-based materials, foam and bamboo reinforced concrete, bio-receptive concrete, and bricks made from pollutants.

The Circular Economy begins in the first phase, the design and pre-construction phase, by intentionally replacing a high intensive carbon proportion of virgin materials with recyclable industrial and consumption waste, which actively supports the reduction of pollutants into the environment (SDG 9), waste of resources, and a remarkable decrease of the AEC sector’s dependence on primary resource extraction (SDG 12) [47,59,64]. Ref. [47] shows the example of the application of Circular Economy in housing; the Development Association for Renewable Energies (DARE) in Nigeria’s used-plastic bottles were full of sand and then connected at the neck by a complex string network, created to strong

construction material 20 times stronger than traditional brick [99]. The use of green concrete materials that contain recycled materials in their components can be seen in the contribution to SDG results, where the percentage of SDG 12 is 92%, SDG 11 and SDG 6 are 85%, SDG 9 is 77%, SDG 8 is 74%, and SDG 3 and SDG 7 are 70% [59], while the investigation of recycle concrete waste advances waste valorisation and environmentally responsible construction, contributing to SDG 11, SDG 12, and SDG 13 [64]. During this stage, engineers specify alternative components such as recycled concrete, tyre rubber and residue fluidised catalytic cracking, while simultaneously designing frameworks to ensure these types of materials can be easily recovered decades in the future (SDG 7, SDG 11, SDG 13) [11,61,65].

In the manufacturing and execution phase, the Circular Economy works by optimising physical material flows and reverse logistics to eliminate on-site waste [10,59,65] physically [10,57,63]. By defining the drivers and barriers to achievement of clean water and sanitation in India to achieve SDG 6, the article recommends some creative solutions, such as prioritising wastewater reuse or Circular Economy principles [10]. By utilising pre-specified recycled aggregates and enforcing strict recycling materials methodologies aimed at bringing materials back into another supply chain (SDG 12), some projects remarkably reduce the total carbon emissions needed to process and transport new virgin materials (SDG 13) [62,64,66]. The use of modified asphalt mixtures that are made of recycled tyres can minimise waste and the exploitation of virgin material, providing a technically and economically viable solution for sustainable and resilient pavement systems (SDG 9, SDG 11) [62]. Another case is the investigation of the physical, mechanical, and microstructural properties of concrete incorporated with recycle concrete waste, resulting in an improvement of 3.84% in compressive strength, 6.25% in tensile strength, 15.32% in flexural strength, and 4.9% in the modulus of elasticity, reducing landfill waste and promoting resource efficiency (SDG 11, SDG 12, SDG 13) [64].

In the final lifecycle phase, Circular Economy principles completely redefine traditional, destructive demolition by transforming it into a strategic material recovery process. For example, Refs. [49,56] focus on the reuse and recycling of construction and demolition waste to minimise environmental impacts (SDG 12), and managing hazardous substances that could cause water pollution (SDG 6). Supported by the structural modularity of modern methods of construction, end-of-life buildings are systematically disassembled and managed through comprehensive construction and demolition waste management strategies [44,51,52]. This deconstruction process considers dismantled structures as new types of material for the next project that restore warehouses safely and supply construction components for projects. By retrieving the huge number of structural materials and preventing them from overwhelming the urban local landfill, this step actively protects urban ecological health and waste infrastructure, directly contributing to SDG 11. Furthermore, by ensuring the end-of-life of one project will turn into the pre-construction phase of another project, this framework permanently closes the resource loop, successfully securing the achievement of SDG 12 [100].

5.1.4. Socio-Digital Enabler

The previous three components examined in this study provide the physical and operational mechanisms for sustainable industrialisation. However, these mechanisms cannot be implemented in isolation. The fourth component of this thematic analysis examines the critical enablers that support the transition, including digital technologies, social equity frameworks and localised governance. Together, these enablers help align technical construction practices with the broader, multidimensional targets of the UN 2030 Agenda.

Firstly, rapid digital transformation in the construction industry is heavily driven by advances in modelling, visualisation, automation and data-enabled decision making. Some technologies that are applied in this sector, such as building information modelling (BIM), virtual and augmented reality (VR/AR), artificial intelligence (AI) and data-centric platforms, are increasingly embedded in professional practice across the project lifecycle [101,102]. Notably, the SDG Digital Acceleration Agenda highlights digitalisation's importance in achieving 70% of the SDGs' 169 targets [103]. Secondly, the transition must account for social enablers, addressing the frequently neglected human dimension of sustainability. In that regard, social sustainability is defined as a pathway to improving the quality of human life that involves enabling social self-determination and preserving cultural diversity, while also providing skills development and creating opportunities for disadvantaged groups.

Furthermore, it also emphasises promoting equity between generations and ensuring a fair distribution of social costs and benefits associated with construction activities. Finally, according to [42], without government support, especially in the construction industry, sustainability might not be completely achieved. It is evident that the government is a key stakeholder in this industry and plays an important role in providing the enabling environment for the effective implementation of sustainable construction [44]. For example, in Ghana, two of the five strongest barriers to implementing sustainable construction are a lack of government commitment and applicable legislation.

During the design and pre-construction phase, Sustainable Leadership Innovation Capability (SLIC) and a five-phase managerial roadmap in organisations enhanced the environment and economic performance along with commercial sustainability (SDG 9, SDG 11, SDG 12 and SDG 13) [41]. According to [32], rigorous sustainable procurement frameworks, including material reuse, sustainable design (SDG 12) and the partnership between government and industry stakeholders, should be applied. Guided by strict Environmental Impact Assessments, project planners integrate geospatial data fusion, artificial intelligence (AI), building information modelling (BIM), enhanced digital twins (EDTs), and information and communication technology (ICT) to digitally map and simulate urbanisation impacts before the execution phase is implemented [33,40,43,46,50,55]. This data-driven procurement planning directly advances SDG 7, SDG 9, and SDG 11 by supporting resilient infrastructure and sustainable urban development. Furthermore, by utilising the socio-digital framework to design and allocate low-cost and resilient housing, it prevents systemic inequalities, directly leading to SDG 1 and SDG 11 [24,58].

In the construction/execution phase, the shift towards time monitoring and labour safety can be seen. Ref. [34] shows the attention of European countries like Spain, the UK, Italy and Denmark to digital integration and urban resilience (SDG 9, SDG 11), while Brazil, India and Malaysia focus on addressing labour practices and resource efficiency (SDG 8, SDG 12). In another case, localised social and governance frameworks are strictly enforced to protect vulnerable labourers by mandatory Personal Protective Equipment protocols, health insurance enrolment and awareness for informal artisans (SDG 3) [35].

In the operation phase, the data level is scaled up from the project level and localised into the national governance system or international benchmarking [45,60]; for instance, China tried to create a sub-index of the development of the socialised national conditions with a multidimensional assessment that depends on Chinese characteristics [42]. Policymakers use ICT pathways to benchmark built environments, enforcing macro-level ecological civilisation targets that drive carbon neutrality (SDGs) [33,37]. Furthermore, Ref. [44] provides a tool for construction- and demolition-caused pollutant assessment that leads to the development of a transition from linear to circular sustainability models in rapidly urbanising regions. Another transition from Industry 4.0 to Society 5.0 also plays

an important role in achieving a sustainable and intelligent global society, while governance needs to address three key issues, including human-oriented action, sustainable development and the physical to digital loop [19].

5.2. Operational Synergies and Trade-Offs of the Four Components' Integration

5.2.1. Operational Synergies of Four Components' Integration

When integrating the four components of sustainable industrialisation, the core components exhibit compounding benefits. For the integration between MMC and the Circular Economy, the most physical synergy can be achieved through the standardisation of MMC and a closed-loop material in the Circular Economy [51,52]. The application of MMC depends on discrete modules and prefabricated components that are connected by physical joints. In the end-of-life phase, it provides exactly the architectural models required for Circular Economy deconstruction rather than extracting structures from cast-in-place buildings. This integration exponentially increases the deconstruction recovery rate, supporting the achievement of SDG 12. Ref. [52] proposed a multi-criteria assessment framework that circularity metrics align with sustainable indicators, offering a more holistic evaluation of MMC products, leading to more informed and balanced procurement of MMC products, and offering benchmarking and standard development within Circular Economy initiatives. Quantitative evidence of sustainability improvements is particularly strong for material efficiency and waste reduction. Ref. [81] developed a comparative framework based on case studies and showed that modular construction can reduce total waste generation by up to 83.2% and waste-related costs by 47.9% in large-scale projects. These results provide quantified evidence of the environmental benefits associated with modular construction methods.

The interaction between lean and prefabricated construction methods can also be seen clearly in five research dimensions in lean prefabricated construction, including data-driven decision-making, process optimisation, sustainability, and integration with other strategies such as Circular Economy and on-site industrialisation. An example of lean improving prefabricated construction is provided by [85], applying a structural equation model and fuzzy evaluation to analyse prefabricated building projects. They identified 23 driving factors and 16 performance indicators across schedule, quality, cost, and safety, and demonstrated that lean practices improve project performance through mechanisms such as modular collaborative design, lean transportation planning, waste elimination, and organisational management. Their results indicate that lean practices influence multiple project performance dimensions simultaneously, while cost performance remains comparatively difficult to optimise.

On the other hand, Lean Management principles such as waste elimination and workflow stability are significantly improved due to the application of Digitalisation. AI, BIM, EDTs, ICT, and geospatial data fusion provide real-time spatial monitoring like distance to roads, city boundaries, and dust-proof nets, to optimise Just-In-Time (JIT) material flows, reflect urban construction more rapidly and accurately, and aim to bring key insights for urban planners [38,40,49]. In this approach, digitalisation eliminates blind spots of management strategies and physical manufacturing before applying them into construction projects, leading to timesaving in the design and execution phase [38]. By simulating spatial logistics and material flows before it is executed on-site in the construction projects, this collaboration prevents supply chain bottlenecks, minimises equipment waiting time on the construction site and drives the resource efficiency target of SDG 9 [36].

Ultimately, the technical and material synergies between MMC and Circular Economy need to be actively catalysed by a combination of strategic corporate governance and aggressive public sector market intervention. This integration is initiated by SLIC in

project-level collaboration to achieve SDG 9 through the integration of digital tools and the development of innovation capabilities, supporting industry modernisation and adaptive capacities. Furthermore, it drives SDG 11 through the examination of how leadership innovation influences responsible construction practices. From an operational perspective, SLIC achieves SDG 12 through the link between green HRM (human resource management), digital technologies, and environmental management systems to more efficient use of materials and energy, and SDG 13 through embedding environmental goals into HRM and the decision-making process [41]. However, willingness alone from organisations is insufficient to scale industrialisation without the transition from governance and stakeholders. Ref. [32] bridged the gap through the implementation of sustainable procurement frameworks. When governance and stakeholders mandate sustainable procurement practices in public infrastructure projects, they effectively force the market to use circular materials and off-site manufacturing. This will mitigate financial barriers to constructing an MMC factory, finally turning sustainable procurement challenges into opportunities that directly fulfil multiple targets of SDG 12. In another case, by using standard, green modules to rapidly replace deteriorating urban infrastructure while simultaneously reconnecting fragmented ecological spaces, this approach successfully mitigates the negative impacts of rapid urbanisation (SDG 11) [48].

5.2.2. Operational Trade-Offs of the Four Components' Integration

Despite the positive synergies between these four components, the systemic integration of these frameworks also introduces severe operational frictions. Firstly, the collaboration between the localised emission reduction of MMC and the carbon footprint of its supply chain logistics can be seen during the material production stage [46]. With the use of energy like diesel and on-site construction, such as high diesel and electricity use on-site, the transportation stage also becomes one of the stages to bring the most negative impacts into the environment. Because MMC relies on the delivery of heavy, fully formed modules, it requires specialised and high-emission road freight. For instance, the transportation stage for precast concrete has been shown to result in a concerning 4% increase in carbon emissions [36].

Despite the synergies between MMC and Lean Management that were demonstrated above, Ref. [86] highlights that most studies analyse lean and prefabrication separately, and that the concept of lean prefabricated construction lacks a consolidated body of knowledge. Ref. [69] similarly shows that, although advanced scheduling and optimisation techniques exist, their implementation in modular construction practice remains limited. It indicates that improvements in efficiency, scheduling, and operational coordination are frequently analysed separately rather than within fully integrated industrialised construction frameworks.

Furthermore, another direct physical conflict exists between the core principles of the Circular Economy and the mechanical requirements of MMC. Automated industrialisation requires high-quality input materials to be mathematically precise and structurally homogeneous to maintain the assembly line speed. However, circular materials such as utilised plastic waste [47], residue fluidised catalytic cracking in lightweight polystyrene concrete [11], or green concrete materials [59] suffer from performance variability and unequal quality. For example, crumb rubber (from waste tyres) has significant variability based on the tyre source, grinding method, and contamination levels, which introduces inconsistencies in concrete performance [65]. The application of these materials will require a continuous examination and an unreasonable cost to ensure compliance with strict safety policies [64,65]. In that case, the application of a Socio-Digital Enabler such as Machine Learning also offers robust control solutions for quality control [44]. Consequently, the pur-

suit of material circularity without a designed management strategy can directly impede the rapid standardisation and efficiency of output required by industrialised manufacturing.

The transition towards sustainable industrialisation, a highly automated and digitalised construction ecosystem, creates socio-economic inequities if implemented without governance and policy awareness. The application of digital technologies or sophisticated management practices heavily favours highly capitalised and big contractors, while in the AEC sector, especially in developing countries, it mostly depends on informal, artisan labour [35]. The research highlights the lax compliance with basic safety awareness and personal protective equipment, and ignorance of the consequences to health from the worker's side. This vulnerability is further exacerbated by the client's reluctance to incur extra costs for safety kits and overall lax supervision of construction sites, as well as lax safety compliance by relevant agencies. If rapid digitalisation is pursued within this environment, it threatens workers' economic status, creating direct conflicts between digital technology developments (SDG 9) and equitable labour inclusion (SDG 8). To reconcile this trade-off, technological modernisation should go with targeted social and governance interventions. Policy frameworks must apply site safety compliance and enforce personal protective equipment protocols [12] and social safety nets, such as appraising artisan health insurance enrolment [35]. By institutionalising these protection approaches, governance ensures that the drive toward industrialisation simultaneously secures SDG 3, ensuring that the modernisation of the AEC sector leaves no vulnerable worker behind.

5.3. Resolving Systemic Barriers Through Stakeholder Engagement and Localised Governance Frameworks

5.3.1. The Role of Stakeholder Engagement

Systemic barriers originally exist because of the separated operations and resistance to change from the whole industry. The participation of many stakeholders, including developers, suppliers, workers, government bodies, and local communities, drives the cultural and operational shifts that are necessary for sustainable industrialisation.

First, overcoming conservative mindsets about Lean Management can be seen in the AEC sector. The supply chain process in this sector has evolved over decades and remains unchanged, while any changes can be seen as a disruptive event that leads to various complications. It can be clearly seen in senior managers, who tend to rely on familiar supply chains and products. For example, Ref. [63] shows the opinion of one participant about his experience of encountering obstacles from the surroundings in utilising old materials, despite the material still being in good condition. It is driven by a prevailing public misconception that old materials are always of low quality and cannot be used, which directly hampers Circular Economy adoption. Lean Management strategies depend heavily on collaborative planning, transparency, and regular communication to overcome this resistance [54]. To overcome this sociocultural resistance, Lean Management strategies are highly effective because they depend heavily on collaborative planning, transparency, and regular communication to drive a cultural shift. By utilising tools like Last Planner System, collaborative scheduling and pull planning, all participants from contractors, sub-contractors and suppliers are actively engaged in decision-making, ensuring that everyone has a clear understanding of the project timeline, resource requirements, and potential constraints. This inclusive approach fosters a sense of ownership, reduces misunderstandings, and culturally shifts the workforce toward continuous improvement and waste reduction.

Secondly, transitioning to a Circular Economy and utilising MMC requires highly integrated supply chains, while contractors always rely on traditional supply chains. Recently, there has been a lack of experience in how to deal with suppliers of circular materials like products with recycled content [51]. Furthermore, there is a mistrust among stakeholders

due to the fear of ‘greenwashing’. According to an interviewer’s worry in this article, drawbacks about the trustworthiness of completely recycled material always exist in this sector; investigators only need test the material and pay a few hundred dollars to verify its quality. Because stakeholders aim to increase their profit and intentionally exaggerate the environmental benefits of their materials, to solve this problem, large stakeholders and contractors must use their market dominance to build strategic partnerships with circular material suppliers, leading to economies of scale and production cost reductions that can bring small enterprises along with them. To ensure the efficiency of the integration between the Circular Economy and modular construction, the article recommends that contracts, such as a product buyback agreements, should be signed between the modular manufacturers and end-users. Mutual benefits can be seen from the end-users’ side; they can increase their revenue by selling unused construction components, while manufacturers can gain an opportunity to recover modular products, ensure that materials will be used till their end-of-life, then recycled into new modules, promoting sustainability and resource efficiency.

Another barrier that can be seen is the financial barrier of integrating MMC and digitisation because of the high upfront capital investment [34]. It is a major obstacle, especially for smaller enterprises and private owners, due to the initial expenses associated with clean technologies such as photovoltaic systems, advanced water treatment units, and sustainable construction materials that make them face funding shortages and opt for cheaper, unsustainable traditional methods [34,63]. Governments and financial institutions should be included as key stakeholders by providing targeted financial incentives such as tax exemptions and subsidies, contributing to the decrease of the initial cost for green technologies [61]. Instead of only focusing on the upfront construction costs, stakeholders need to adopt Whole Life Cost assessments that are currently applied by only 5% of the private sector, aiming to demonstrate to investors the long-term operational savings of sustainable buildings [32].

5.3.2. The Role of Localised Governance Frameworks

Because of the global application of the SDGs, it is too broad and fails to apply to specific infrastructural, economic and institutional capacities of different regions, particularly the differences between developing and developed countries [43,58]. Localised governance bridges the gap by translating policies into highly specific urban planning schemes, building codes and green standards. For example, in China, Ref. [37] established a connection between the SDGs and efforts in ecological civilisation construction by developing a set of indicators that evaluate practical performance suitable with Chinese characteristics. This tailored approach directly aligns with MMC, Lean Management, circular practices, and Socio-Digital Enablers within that specific local environment, ensuring that global targets are practically actionable in those applied regions.

Transitioning to circular materials and MMC involves significant financial barriers and market uncertainties for smaller enterprises because traditional and linear construction methods are cheaper and more familiar with managers, as demonstrated above [32]. From the government side, they can be considered as a big consumer for industrial and construction activities for critical and public infrastructures. By issuing Green Public Procurement policies, local authorities can encourage the use of circular materials, low-carbon technologies and MMC in public projects [32,52], creating a guaranteed market demand that mitigates the financial risks for private companies. In Aalborg, Denmark, the local municipality acted as the building owner in the construction of a new school and a day care centre for kids aged 0–15 years called ‘Kids and Youth Universe’ [8]. Through localised governance, the Circular Economy was implemented successfully by mandating the use of

reused bricks from local markets that were collected from old, demolished Danish buildings. This plan effectively forces the local supply chain to support circularity and standardise sustainable practices from the initial vision plan.

These financial problems also exist in the transition to highly digitalised and automated construction, which demands substantial upfront capital investment. Besides introducing local tax exemptions, subsidies, expedited permitting, and regional green bonds, local governments can build a reliable ICT infrastructure that enables examining the new strategies for managing urban infrastructures [43]. This financial safety net allows local contractors and smaller enterprises to afford the initial costs of socio-digital tools and sustainable materials, ensuring that economic constraints do not prevent the transition to a sustainable urban environment.

Another major obstacle to sustainable industrialisation is the lack of collaboration between government ministries and departments [63]. This institutional fragmentation leads to conflicting regulations, unnecessary delays and a lack of law and policy implementation across the industry. This problem is exacerbated by the shortage of technical personnel at the local regulatory offices, leading to the improper supervision from local governments of sustainable construction or enforcing green standards. A robust local governance framework establishes multi-level resilience by actively breaking down the fragmentation of these departments and is expected to provide a cohesive and conducive environment for digital transformation and SDG attainment [43]. By ensuring that policies related to waste management, digital infrastructure, and urban planning are harmonised, local governments allow Lean Management and circular construction projects to proceed efficiently.

6. Discussion and Future Works

The paper set out to establish a comprehensive, multi-dimensional framework demonstrating that sustainable industrialisation in the AEC sector cannot be achieved through isolated physical or technological practices. The process of achieving sustainability in industrialisation only succeeds at the intersection of four key components, including MMC, Lean Management, Circular Economy and Socio-Digital Enablers. While the physical implementation of standardised MMC modules provides the necessary infrastructure for a closed-loop deconstruction [51,52] that supports the use of the Circular Economy, it remains vulnerable without real-time data monitoring [38] and robust institutional governance [44]. The thematic analysis highlighted a critical socio-digital gap in advanced digital tools like BIM, AI, EDTs, and ICT that significantly optimises supply chain and macro-level urban planning [38,40,43], but it also creates inequity due to capital investment and threatens smaller enterprises' economy and artisans' resources. Furthermore, the operational tension between the geometrical and structural precision demanded by automated MMC and the inherent performance variability of circular materials such as green waste or residue fluidised catalytic cracking reveals that material circularity can lower manufacturing efficiency [11,59,64]. Resolving these systemic trade-offs requires shifting from fragmented project management to integrated, localised governance frameworks. The proactive engagement of stakeholders, aligned with governance policies, will serve as the ultimate mechanism to transform these operational frictions into compounding, sustainable gain across the project lifecycle.

The methodological design of this review offers several strengths. Firstly, the use of two leading databases (Scopus and WoS), adherence to PRISMA 2020 guidelines, and the structured content analysis of selected literature ensure methodological transparency and replicability. By combining qualitative synthesis with 42 recent studies across four core stages, MMC, Lean Efficiency, Circularity and Digital Enablers, this approach enhances

both the breadth and interpretive depth of the findings regarding the AEC industry's shift toward sustainable industrialisation.

However, certain limitations must be acknowledged. The dataset primarily comprises peer-reviewed studies published in English that focus on the construction sector and the SDGs. This focus may inadvertently exclude relevant sustainable practices such as specific advancements in prefabrication, modular construction, assembly construction, or lean manufacturing that are not explicitly framed in SDG terms. Additionally, the time period researched was restricted to recent publications from 2022 to 2026, which successfully captured the latest post-pandemic technological advancements but excluded earlier foundational research. It highlights the need for a broader and more inclusive approach to the evidence in future scientific research. Ultimately, recognising these boundaries informed the development of a four-stage strategic roadmap that is proposed in this study, aimed at strengthening the integration of different types of modern methods of technology currently applied: Lean Management planning, the Circular Economy and policy localisation across diverse global contexts. Furthermore, the systematic search was exclusively confined the Scopus and WoS databases. While prioritising these ensures the synthesised data is derived from high-impact, rigorously peer-reviewed literature, this exclusivity introduces a potential database selection bias. The screening tool was strictly limited to English-language publications, introducing an inherent geographic and language bias, potentially missing significant advancements in sustainable industrialisation originating from non-English speaking regions.

To advance the transition of sustainable industrialisation and resolve the systemic barrier that was identified in this study, future research must investigate the transition of sustainable industrialisation under climate change scenarios, such as floods or hydraulic scour, to examine the integration of the four components in these destructive events. Furthermore, future works should directly evaluate localised policy efficacy by addressing policy misalignment and fragmentation and quantitatively test how different regulatory interventions and harmonised policies perform across diverse cultural contexts. To overcome market uncertainty, research must establish viable business models tailored only for modular construction, with a strong emphasis on design for disassembly to enable closed-loop material recovery at the end-of-life stage. To mitigate the financial problems in small enterprises, future work should also focus on making advanced digital tools financially viable for projects with low cost and leveraging big data analytics to improve real-time circularity assessments.

7. Conclusions

This study has systematically investigated the transition of the AEC sector toward sustainable industrialisation. It started with the PRISMA method to select the appropriate articles to be included in the study, by identifying, screening, filtering and determining eligibility for final inclusion. Then, it used Biblioshiny (R-package) and VOSviewer to visualise co-authorship networks, keyword co-occurrence and thematic clusters. In this step, four components of sustainable industrialisation can be defined clearly. The next section represents the core analytical findings, directly answering the research questions that were defined in Section 2. It details how the four components work separately and together, the synergies and trade-off relationships of this integration, before identifying the barriers hindering industrialisation, showing how stakeholders and localised governance frameworks are essential to resolve them. Finally, this study pointed out the limitations and strengths, then recommended future research directions, emphasising the critical need for climate change frameworks, localised policies, and business models to achieve comprehensive sustainable industrialisation as well as SDGs.

Overall, this study contributes a comprehensive and integrated framework for understanding sustainable industrialisation in the AEC sector, particularly:

- Expanding the framework to achieve SDGs and sustainable industrialisation of the AEC sector depends on four main components: MMC, Lean Management, Circular Economy and Socio-Digital Enablers;
- Identifying synergies and trade-off relationships between four components, then defining the obstacle that prevents that integration;
- Providing decision-support tools for stakeholders, including contractors, manufacturers, architects and clients;
- Recommending tailored practical policy roadmaps for implementing targeted interventions.

Supplementary Materials: The following supporting information can be downloaded at <https://doi.org/10.17605/OSF.IO/ABPNJ>, Research Repository [104] and <https://www.mdpi.com/article/10.3390/app16136560/s1>, PRISMA 2020 checklist. Reference [105] is cited in the Supplementary Materials.

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