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Systematic Review

Integration of Building Services in Modular Construction: A PRISMA Approach

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Abstract: Modular construction is gaining worldwide attention. Building services are the systems that make buildings comfortable and efficient. Mechanical, electrical, and plumbing (MEP) systems provide heating, cooling, lighting, energy distribution, and water services. Modular construction integrates building services into prefabricated modules at the manufacturing site, which are then transported to the construction site. A systematic review (SR) of building services integration within modular construction is thus necessary. Prior to the SR, a quantitative analysis of the retrieved 115 publications from the Scopus database was explored. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guide, 13 relevant publications from the Scopus database and via the Research Rabbit application were profiled. MEP systems integration approaches and research needs were examined. Recent literature emphasizes technology integration and sustainability, while early studies laid the framework for modular approaches. The findings highlight the potential of digital technologies like building information modeling (BIM) and recommend a holistic framework for the entire building's lifetime, from design to operation. Future research directions include performance studies, modular building service adaptation, and industry-wide standards building. Researchers and practitioners seeking to improve modular construction methods and integrate complex building services will gain insights from this study.

Keywords: BIM; building services; integration; modular construction; MEP systems; prefabrication

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1. Introduction

The construction industry is moving from high consumption, low output, and low productivity to high-quality products and modern procedures to address sustainable growth [1]. Also, the construction industry, recently focusing more on prefabrication and modularization, has excellent potential to contribute to a better society [2]. However, the unpredictability of prefabricated structures' thermal performance and energy efficiency leads to a considerable amount of unneeded expenditure in the form of additional material, labor, and transportation expenses [3]. Building services engineering focuses on planning, installing, operating, and supervising mechanical and electrical systems within buildings. The central systems are heating, ventilation, air conditioning (HVAC), water, plumbing, drainage, lighting, automation, security, and alarm systems [4].

Similarly, realizing operational building systems and components depends heavily on building control systems for heating, ventilation, and air conditioning (HVAC) [5]. Likewise, one off-site construction technology that can significantly increase productivity is the prefabricated mechanical, electrical, and plumbing (MEP) module [5]. However, different limitations do arise in the prefabrication of MEP modules. For instance, two main constraints that can occur while building MEP rooms are space constraints and scheduling delays—these elements usually result in poor production, delays in plumbing installation, space conflicts between subcontractors, safety concerns, and increased costs [6].

Terminologies like prefabrication, modular construction, and off-site construction are used interchangeably and refer to different approaches and systems, and the complexity of the assembled components determines which system is utilized [7]. Likewise, there is a lack of consistency in off-site system classification. According to Ayinla et al. [8], classifications are primarily targeted at a specific purpose; existing classification systems are not robust enough to cover all aspects, and these classification systems must be extended to suit various purposes. Furthermore, modern methods of construction (MMC), a term coined by the UK government [9], include all the approaches that aim to optimize the construction process to obtain better products in less time. MMC is defined differently in other countries, with Asia using prefabrication, modular integrated construction, or industrialized building systems, and the US and Australia preferring off-site construction (OSC) techniques [10]. MMC's key pillars are business efficiency, quality, user satisfaction, environmental performance sustainability, and delivery timescale predictability. Although MMC offer many benefits, their uptake is low [11], and MMC include but are not limited to OSC. In this study, the term modular construction will be used.

Modular construction entails adding significant value to a product by manufacturing and pre-assembling components, elements, or modules in a factory before installing them on-site. Off-site preassembly, hybrid systems, panelized systems, and modular construction are some of the most effective approaches to overcoming current construction industry challenges [12]. The lifecycle of the modular construction process includes digital design, estimation, logistics, manufacturing, assembly, and management. According to [13], innovative competitiveness and sustainability have the most significant driving controls and lowest dependencies, indicating their primary importance in modular construction adoption. In addition, finance, awareness, use of BIM, and belief in modular construction are the major influencing factors in the construction industry [14]. Likewise, modular construction requires advanced infrastructure [15]. In addition, the adoption of modular technologies in housing projects depends on the availability of an attribute-based assessment and selection system [16]. Cost overruns and scheduling issues are also common in the construction industry, as are demands for products that are faster, cheaper, and of significantly higher quality [17].

There is a need to identify studies exploring modular integrated constructions and presenting their findings on integrating building services in modular construction. Therefore, this study focuses on integrating building services in modular construction, which aims to improve modular buildings' efficiency, quality, and sustainability. The study aims to (1) examine the evolution of research trends in building services applications in modular construction and (2) evaluate the existing literature on building services integration within modular construction, focusing on methodologies, key findings, and gaps in current research.

Overview of Building Services Integration

The connection between building services and modular construction involves integrating crucial HVAC, electrical, and plumbing systems into prefabricated modules. According to Bertram et al. [7], modular construction frequently uses pre-installed utilities or designs that facilitate straightforward connection during assembly. This junction, which focuses on integrating the intricacy of building services with the speed and efficiency of modular construction, is a critical space for innovation. Thermally activated building systems (TABS), for instance, have demonstrated economic viability for building heating and cooling by integrating the building structure as thermal energy storage into the building services concept [18].

Buildings are among the world's primary energy consumers and contributors to carbon emissions [19]. Thermal comfort and ventilation are provided by building energy and services systems such as HVAC, lighting, and plug-loads [20]. Meanwhile, defining an ideal indoor climate during design is critical to a building's performance since it affects the comfort of its inhabitants and is critical to its energy consumption and sustainability [21]. Most buildings and the HVAC systems installed within them aim to create a suitable climate that does not negatively impact the occupants' performance or health [21]. As Sihn et al. [22] pointed out, energy-efficient buildings can save costs. For instance, HVAC systems are an essential component group in buildings since roughly 50% of a building's energy consumption is related to HVAC systems [23]. At the building operation stage, accurate system operation data are crucial for optimizing the HVAC system control strategy and analyzing building energy-saving potential [19]. Similarly, integrating the service systems and their parts into the structural and architectural designs and coordinating them helps prevent major roadblocks before building [24]. Figure 1 illustrates a comprehensive framework for building services engineering, highlighting the key components and their interactions within the operational environment.

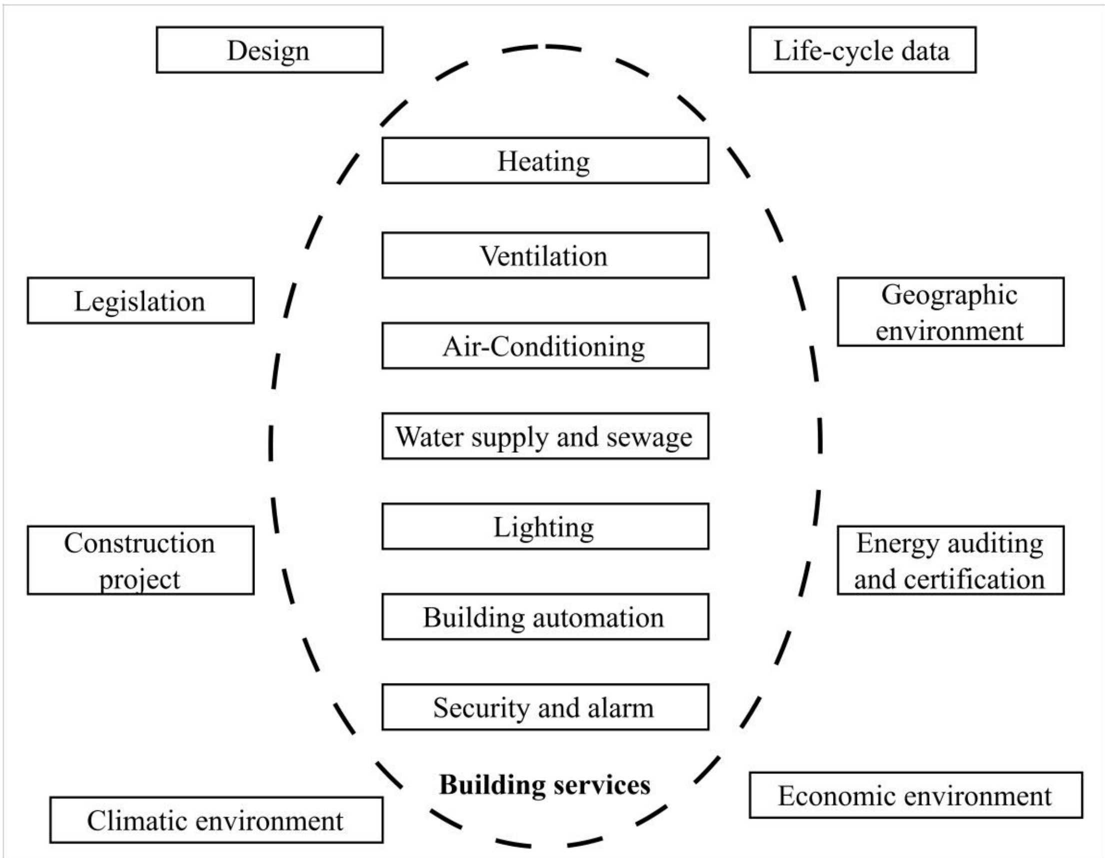

Figure 1. Building services engineering framework adapted from [4].

The framework collectively represents a holistic view of building services engineering, where the successful implementation of these systems requires consideration of design principles, legislative compliance, climatic adaptations, life cycle sustainability, and, more recently, technology and methods such as AI, BIM, IoT, and modular construction.

2. Materials and Methods

To achieve the study's aim, a systematic review (SR) is employed. SR involves conceptualizing the study, establishing a search strategy for related information, extracting relevant data, analyzing the data, and reporting the findings. This study employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guide by [25].

This study's SR of literature on building services integration is appropriate for the following reasons [26–30]:

1. SR analyses current research, evaluates scientific contributions, and synthesizes critical facts;
2. Although a time-consuming and resource-intensive process, SR helps understand the best available evidence on a topic;
3. It identifies, summarizes, and discusses current applications of the subject area.

Any systematic study must prioritize data retrieval [26]. The research approach's data retrieval step is followed by an SR [31]. This study used Scopus bibliographic data, one of the numerous data collection databases. Other prominent databases include WoS, Google Scholar, ScienceDirect, and Dimensions. Scopus was chosen because it has broader coverage and is a good literature review search engine [32–34]. In addition, the Scopus database has high standards and vast coverage in building construction information acquisition [35]. Figure 2 illustrates the study flowchart, and Figure 3 shows the PRISMA records selection flowchart.

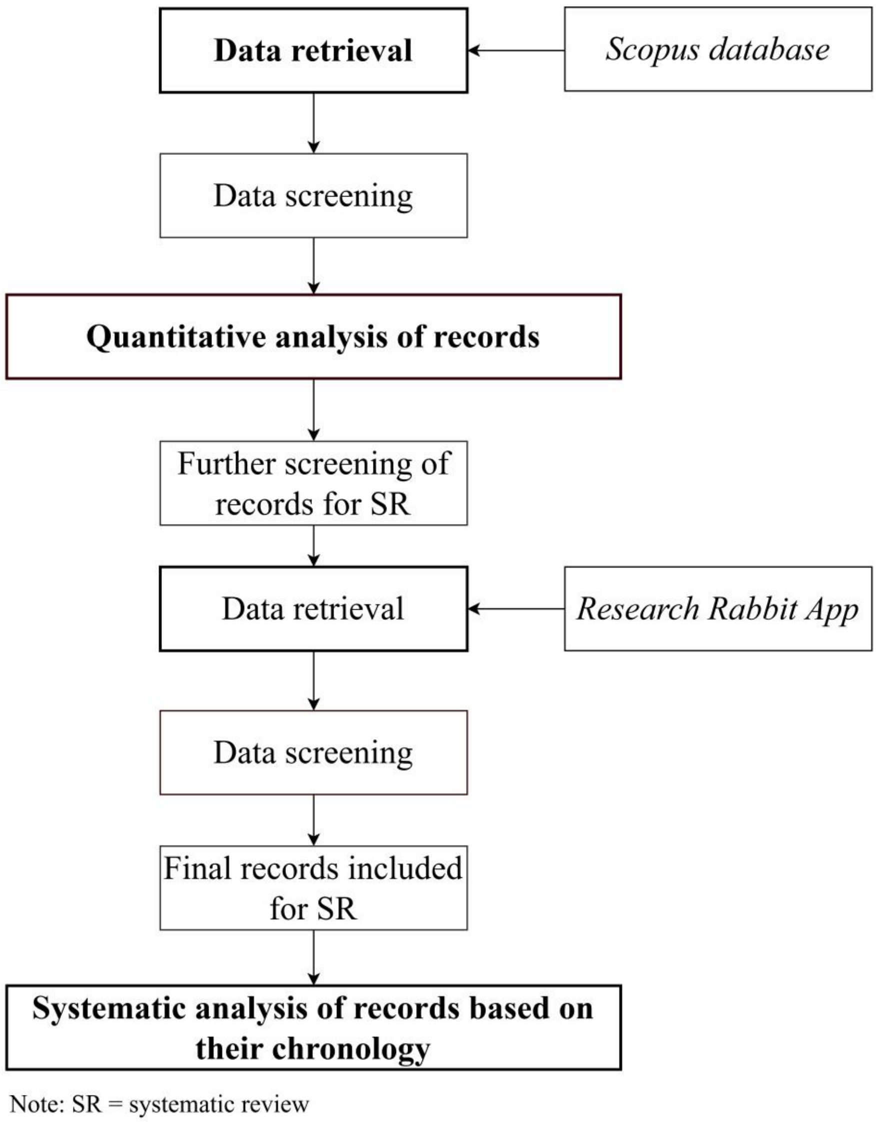

Figure 2. Study flowchart.

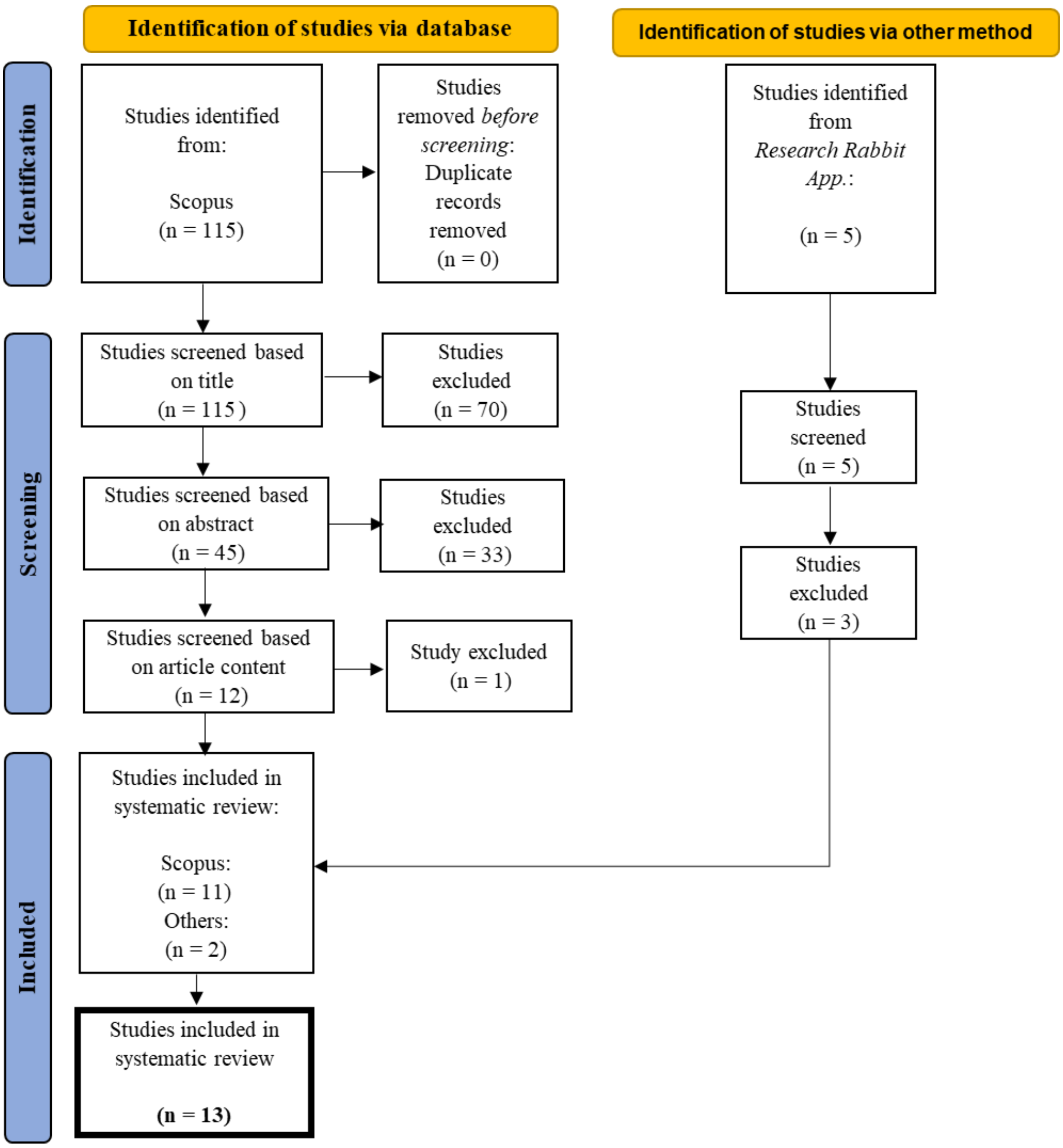

Figure 3. PRISMA selection flowchart.

Figures 2 and 3 illustrate the systematic process employed in the study. The outlined methodologies ensure that the review is comprehensive, methodological, and reproducible, which are essential criteria for scientific investigations. Figure 2 depicts the overall study flowchart, encompassing data retrieval and quantitative and systematic analysis of the retrieved information. In contrast, Figure 3 depicts the PRISMA selection flowchart, which includes study identification, screening, and inclusion.

The search keywords utilized by [26] were applied with minor modifications on the Scopus database to retrieve research articles about modular construction. Similarly, additional keywords were entered to obtain pertinent studies on HVAC, building systems, MEP, building services, facility management, and building utilities. The "AND" operator was then used to combine the two sets of search terms. Moreover, engineering, journal articles, and English were selected as the subject area, document format, and language, respectively. This is how the generated search query appears: *(TITLE-ABS-KEY: "off-site construction" OR "modular construction" OR "prefabrication construction" OR "modular integrated construction" OR "modular buildings" OR "prefabricated building" OR "offsite construction" OR "precast concrete building" OR "precast construction" OR "prefabricated housing" OR "off-site manufacturing" OR "offsite manufacturing" OR "volumetric construction" OR "modern method* *of construction") AND (TITLE-ABS-KEY: "Building Services" OR "Facility Management" OR "Building Utilities" OR "Building Systems" OR "MEP" OR "Mechanical, Electrical, and Plumbing" OR "HVAC" OR "Heating, Ventilation and Air Conditioning") AND (LIMIT-TO: "ar") AND (LIMIT-TO: "j") AND (LIMIT-TO: "English")*. Upon completion of the search, this query yielded 115 publications.

Additionally, an effort was made to use comparable search terms to extract relevant studies from the WoS database. Nevertheless, a comprehensive inspection revealed that the detected results were merely a part of Scopus's results. Scopus database was used because it is found to have broader coverage than other databases [36–39]. Thus, for the overview of modular construction and building service integration, the study used 115 results from the Scopus database. In addition, the abstract, title, and full text of each of the 115 publications were considered when screening them. This study excludes gray literature to ensure reliable, peer-reviewed findings [4]. Gray literature is rarely peer-reviewed or referenced [40]. Gray literature, authored by individuals who may lack academic training or a desire to publish in scholarly publications, can be valuable for verifying the findings of a research-based literature search [40,41]. Nevertheless, the intricate nature of gray literature poses challenges regarding exploration, categorization, organization, and inclusion in the review process [42].

The SR included studies that provide insights into modular building fabrication, design, and construction processes, focusing on MEP and HVAC systems. These criteria were established to gather research on integrating essential building services within the modular construction framework, highlighted as critical for improving the efficiency and effectiveness of this construction approach [4]. Furthermore, integrating MEP and HVAC systems into modular modules is critical since it affects the building's general efficiency, sustainability, and livability.

Furthermore, publications that did not directly address the integration of building services in modular construction and instead concentrated on seismic performance and structural designs of modular buildings were screened out from the SR's list. After the screening, 11 publications were designated for the SR based on the criteria above. The Research Rabbit program was utilized to browse the themes of 1560 similar articles to find other relevant studies related to this study. Only five relevant papers, two of which are included in this SR, were downloaded and examined. This study included 13 studies that were profiled for the SR. To achieve the first objective of this study, 115 Scopus studies were quantitatively reviewed before the SR. The subsequent sections provide the findings.

3. Results

3.1. Quantitative Analysis of Publications in Modular Construction Building Services

The distribution of the publications and their evolution per frequency is first discussed. Figure 4a shows the distribution of modular construction and building services research articles across academic journals, whereas Figure 4b shows the annual frequency of publications. Figure 4a shows a focused output in a few journals, with *Automation in Construction* leading with ten articles. *Journal of Building Engineering* and *Engineering Structures* have eight and six publications, respectively. Other notable contributions come from *Buildings* and *Construction and Architectural Management*, each with five publications. Figure 4b shows a rising publishing trend, indicating a growing awareness of modular construction services. Few publications were made in the early years. However, the subsequent years have seen a rise, peaking at 17 publications in 2023.

Figure 5 shows a modular construction building services literature keyword co-occurrence network. The network is divided into color-coded topical research groupings. The "Integration" cluster is the only one containing many building services keywords. This cluster includes "building information modeling," "digital twin," and "integration" itself, showing a strong research focus on information management and technology intersecting with modular building processes. The timeline gradient at the bottom of Figure 5 shows research themes from 2010 to 2025. The "Integration" cluster emerged later in the timeline, highlighting its expanding prominence in the discipline. This suggests that incorporating building services into modular construction has gained research impetus due to technical advances and a focus on efficiency and coordination.

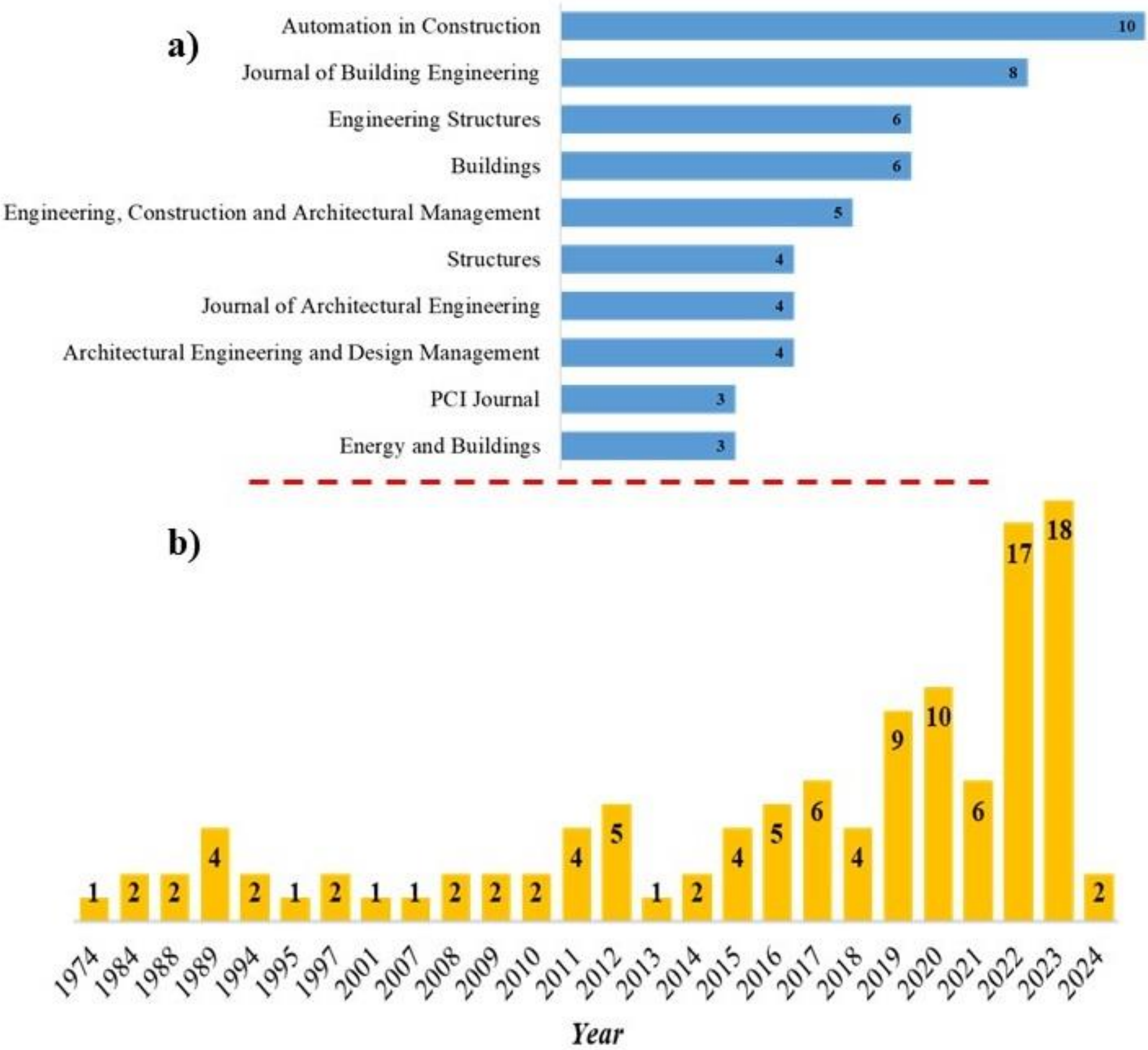

Figure 4. (**a**) Distribution of publications by top ten *journals*; (**b**) Evolution of publication frequency over *time*.

Figure 6 also shows the Scopus citation frequency for modular construction research articles as of December 2023. The collection's most referenced article, "Life Cycle Design and Prefabrication in Buildings: A Review and Case Studies in Hong Kong," has over 200 citations, demonstrating its influence. Both "Design issues of using prefabrication in Hong Kong building construction" and "Steel concrete composite systems for modular construction using BIM-based buildings," with 181 and 128 citations, also significantly influence the research corpus.

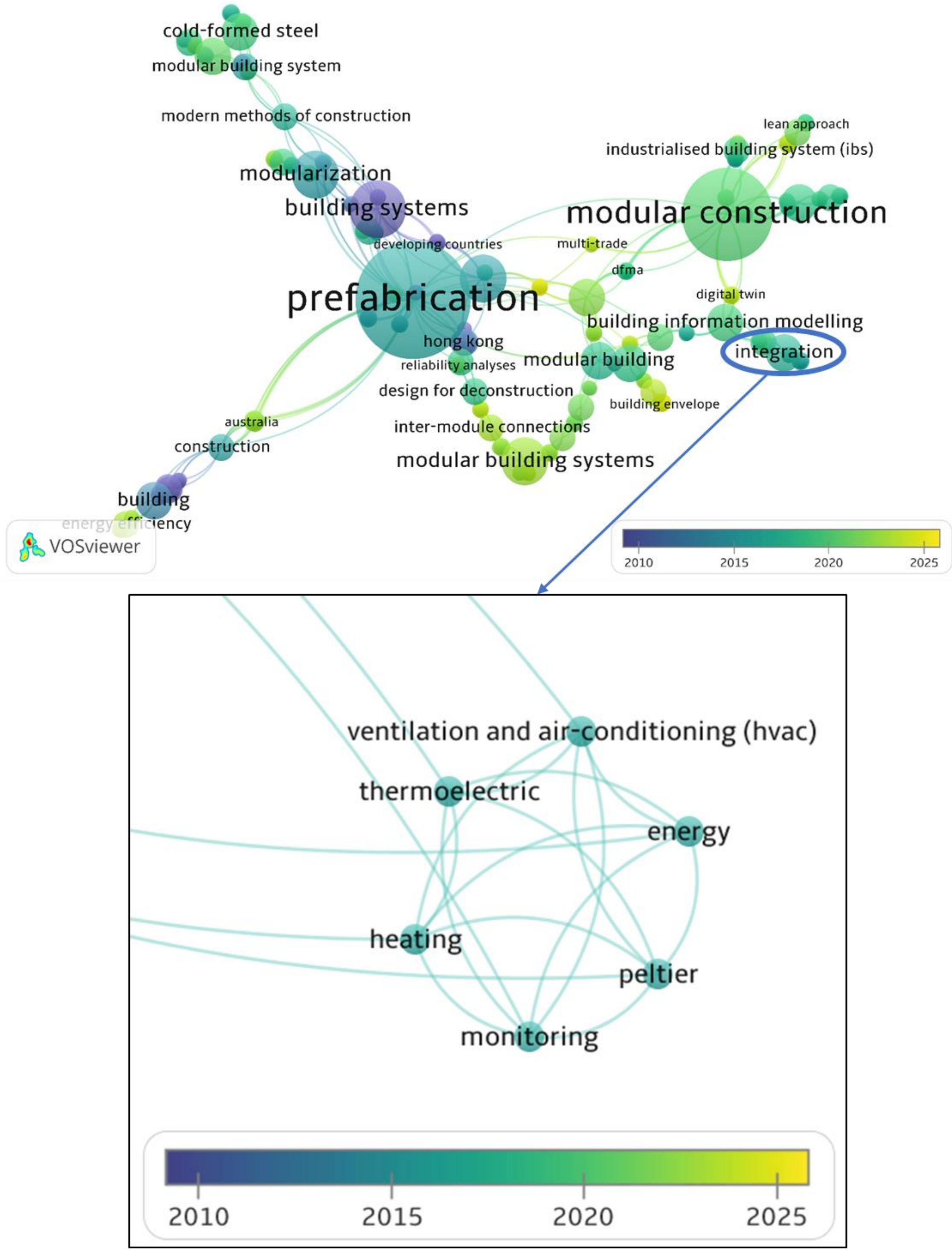

Figure 5. Keyword co-occurrence and cluster analysis.

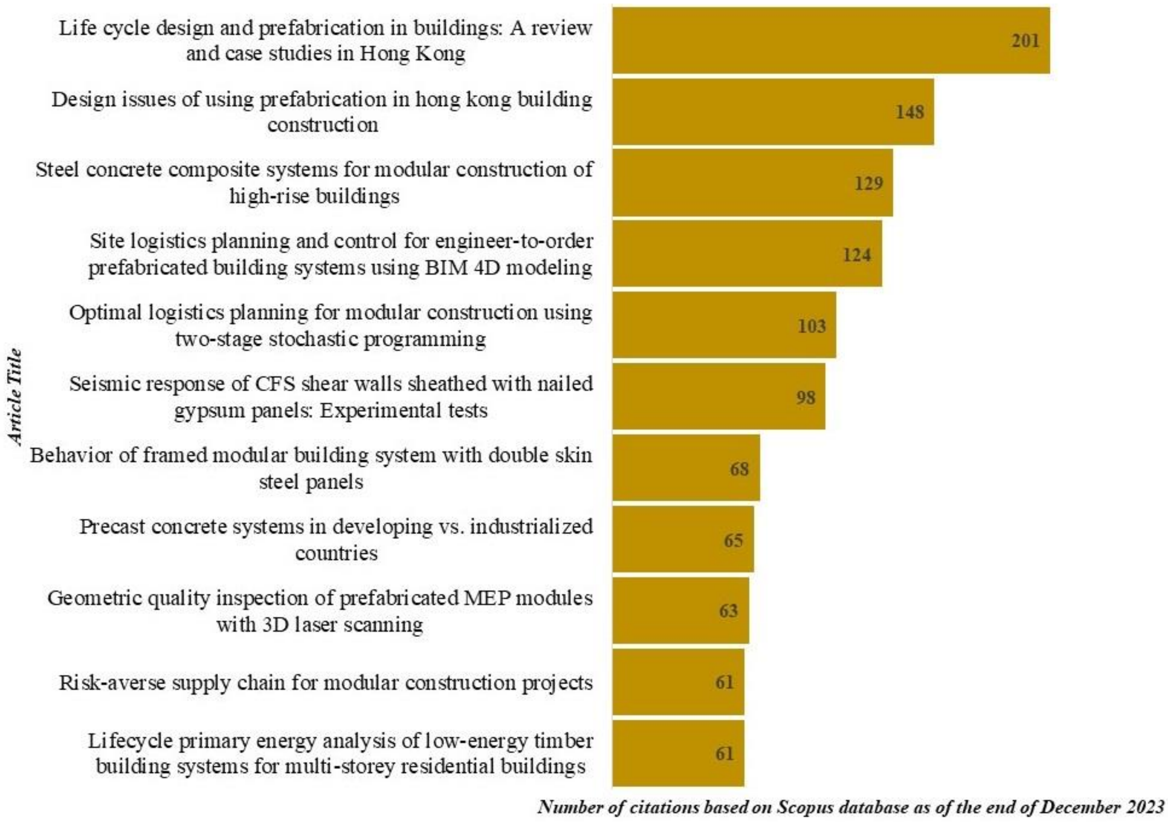

Figure 6. Citation frequency of top-cited articles.

As seen in Figure 6, the article with the highest citation counts focuses on life cycle analysis, design, and prefabrication techniques, and integrating building information modeling (BIM) within modular construction processes. The prevalence of citations in these topics suggests they are critical areas of interest and research.

A rough estimate of keywords on building services was selected from data from the keyword co-occurrence network (see Figure 5) to preview the ratio of these keywords to the total publications used in this study. Two intriguing trends were discovered. First, the overall link strength for selected keywords is 200, reflecting the degree of linkage between these keywords in the literature. 'All Keywords', on the other hand, has a significantly greater link strength of 2740, indicating a more prominent, integrated research topic. Figure 7 depicts a similar gap in the occurrences of these terms, with the selected keywords appearing 41 times and 'All terms' appearing 542 times. While modular construction has become a well-researched issue, the subset of selected keywords related to building services integration occurs less frequently, indicating a more narrow or emerging study area within the broader field.

Figure 7 depicts the frequency of keywords appearing in the study literature. With seven linkages, the most commonly recurring term is 'industrialized building system', followed by 'heating, ventilation, and air conditioning (HVAC)' with three. This is followed by 'modular building systems' and 'building systems', appearing twice. The remaining keywords, which include terms directly related to building services like 'prefabricated MEP module', 'modular floor system,' and 'building services', have only one occurrence.

The analysis indicates that 'selected keywords' (related to building services in modular construction) are less prevalent in the research landscape than other topics. The low occurrence and link strength of these keywords compared to the aggregate suggests a potential research gap in integrating building services within the field of modular construction. While there is considerable research activity around modular construction, the intersection with building services requires more exploration and documentation, which presents opportunities for future studies.

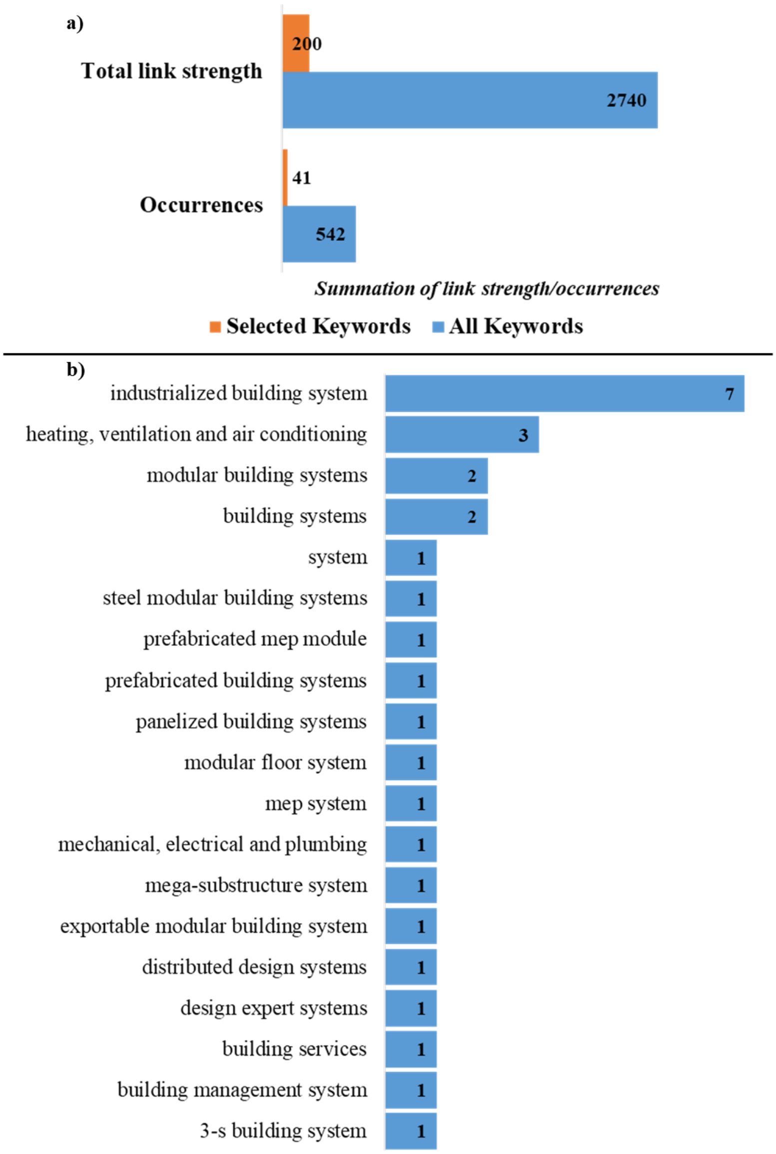

Figure 7. (**a**) Keyword link strength and occurrences analysis; (**b**) Specific keyword focus.

3.2. Systematic Analysis of Integration of Building Services in Modular Construction

3.2.1. Overview of Included Studies

Previous research has interpreted and defined prefabrication (also called modularization) differently based on its subtle regional, geographical, or proximal aspects [43]. Modular construction entails designing, manufacturing, transporting, and assembling building components for rapid site assembly with faster completion than on-site construction [44]. Modular construction has more significant design repercussions from construction issues than traditional ones, making design aspects crucial [45]. Despite delays, cost overruns, and safety issues in the conventional construction industry [46], with the advantages of higher construction speed, productivity, and quality control, modular construction has been adopted in various countries for various construction projects in the past two decades [47,48]. It is safe to say that the construction industry is moving toward modularization, where most work is performed in the factory, and on-site work is significantly reduced [49], demonstrating the benefits of enclosed, climate-controlled factory operations [50]. Table 1 summarizes the title, methodology, and practical applications of the publications included in the SR. Four categories—"early studies", "emerging trends", "recent advances", and "current and future directions"—were used to discuss the results of the publications in this SR in detail. As seen in Figure 8, the classification was based on the chronological overview of the relevant studies [51].

Table 1. Overview of Related Studies.

Study's Title	Methodology	Application/Objective	Reference
Optimising Modularity of Prefabricated Residential Plumbing Systems for Construction in Remote Communities	• Literature review and experts' interview • Prototype design	The study examines multi-trade prefabrication, which combines mechanical, electrical, and plumbing services into a single module for off-site and on-site installation.	[52]
Precast Concrete Floor Framing Systems to Accommodate Nonstructural Requirements	• Literature review • Experts interviews	The study examined modular off-site construction for piping systems, an essential part of building services.	[53]
Thermoelectric cooling heating unit prototype	• Simulation and data analysis • Prototype design	The study analyses the prototype's design, assembly, and energy behavior and its pros and cons compared to traditional HVAC systems.	[54]
Obstacles Preventing the Off-Site Prefabrication of Timber and MEP Services: Qualitative Analyses from Builders and Suppliers in Australia	• Expert interviews, content analysis, and data analysis	The study recommends early involvement, collaborative procurement, digital tools, modular coordination, and system development for integrating off-site prefabricated timber and MEP services with in situ construction.	[43]
Economic Integrated Structural Framing for BIM-Based Prefabricated Mechanical, Electrical, and Plumbing Racks	• Case study and data analysis	The study examines multi-trade prefabrication, which combines mechanical, electrical, and plumbing services into a single module for off-site and on-site installation.	[47]
Modular and Offsite Construction of Piping: Current Barriers and Route	• Mixed methods: qualitative and quantitative data collection and analysis	The study examined modular off-site construction for piping systems, an essential part of building services.	[44]
Simulation-Driven Design of Wood Framing Support Systems for Off-Site Construction Machinery	• Simulation, data collection and analysis, and cost-benefit analysis	The study offers strategies for enhancing off-site production efficiency and performance.	[50]
Steel concrete composite systems for modular construction of high-rise buildings	• Literature review and thematic analysis • Prototype design	This study integrates building services into the modules' structural zone, utilizing a slim floor system to reduce the floor-to-floor depth and assure service compatibility with varying module sizes.	[48]
Investigating the disparities between experimental and computational analyses of thermal performance in prefabricated wall panels	• Experiments, simulations, and thermal performance comparison	The study investigated the thermal performance of prefabricated wall panels, commonly used in modular buildings.	[3]
Geometric quality inspection of prefabricated MEP modules with 3D laser scanning	• Data collection and analysis	The study used 3D laser scanning to inspect prefabricated MEP module geometry.	[49]
Building HVAC control knowledge data schema—Towards a unified representation of control system knowledge	• Data collection and analysis	Using the study's data schema, a control self-configuration framework that interacts with a database of control modules to select and apply building system-specific control strategies can be developed.	[5]
Modularisation and assembly algorithm for efficient MEP construction	• Case study, data analysis, and experts' interview	The paper discusses the benefits and challenges of modular construction and presents a case study of applying the algorithm to a fire suppression system project in Taiwan.	[6]
Construction problems such as tiling puzzles	• Data collection, logical and combinatorial methods	Mathematical theory of tilings for modular construction.	[45]

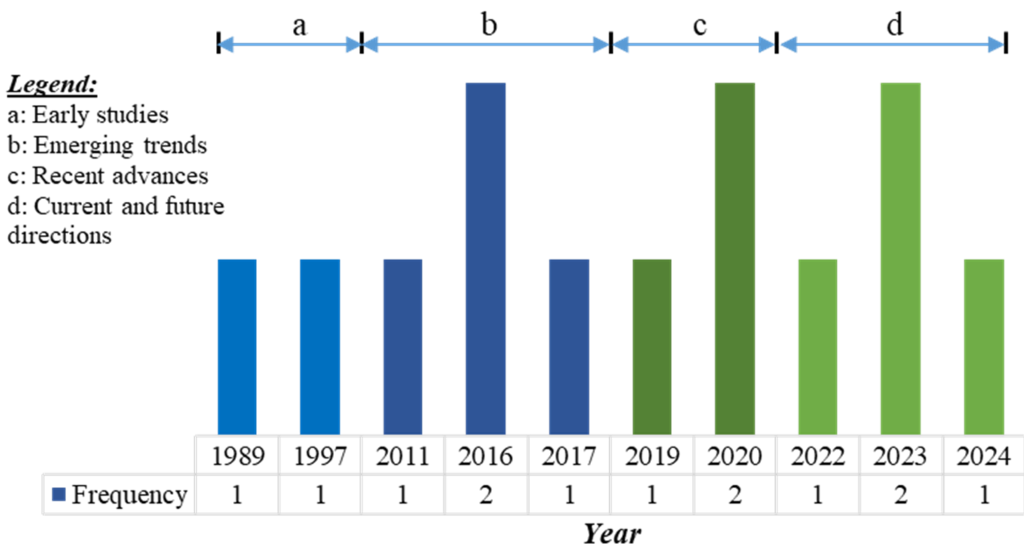

Figure 8. Chronological categorization of included studies for SR.

Figure 8 shows the distribution and frequency of publications on integrating building services in modular construction from 1989 to 2024.

3.2.2. Building Services Integration within Modular Construction

- **Early studies**

Lenart [45] compared construction design and building puzzles, focusing on modular building systems. The research demonstrated how solving tiling difficulties might yield fresh perspectives and approaches to creating patterns and building components. The paper reviewed a few ideas and findings from the mathematical theory of plane tilings, including periodic, non-periodic, monohedral, and isohedral tilings. The study examined their uses and how they affected floor, wall, and architectural facade coverings.

Further, in this category, Slaughter et al. [44] developed a set of criteria for structural floor framing systems created to consider non-structural requirements like service, enclosure, finish, and spatial and functional systems. The criteria offer precise measurements for comparison and assessment and center on the effectiveness and performance of the non-structural systems impacted by the structural system. By better meeting the non-structural requirements, the study found substantial chances to enhance the efficiency and performance of the current precast concrete floor systems. The criteria were utilized to evaluate the systems. Additionally, new concepts for precast concrete floor systems that specifically address the non-structural needs and offer increased spatial and functional diversity were developed using the criteria from the study.

The study developed several novel design concepts for precast concrete floor systems, including the University of Nebraska System, PD2 Frame, and Dyna-Frame. These ideas seek to extend the span, decrease floor depth, provide service system apertures, and enhance floor system fire safety. Using full-scale prototypes, the study investigated a few innovative design concepts to assess their constructability, structural performance, and serviceability. Comparing the new concepts to traditional precast systems, the testing showed they could cut construction time and cost while still meeting the required load capacity, deflection, and vibration standards. The study also found areas where the new design concepts may be improved even further, like strengthening the fire resistance, improving the connecting details, and making the floor systems more adaptable.

- **Emerging trends**

Tserng et al. [6] developed an algorithm for planning, producing, and installing complicated, expensive, and time-consuming building MEP systems. The 3D graphics and spatial planning algorithm breaks the complex MEP system into simple fabrication components. Size, weight, and location are optimized for job site delivery and installation. The algorithm also considers the work site's space, equipment, time, and safety constraints. A logical planning strategy improves MEP facility building efficiency and quality. Three experts validated the algorithm, and a Taiwanese fire suppression system project showed its efficacy and applicability. Chen et al. [5] presented a modularized data structure for building control knowledge (BCK) representation to standardize and simplify HVAC system control logic, algorithms, and sequences. The data schema has eleven elements: control module name, control objective, operation mode, system schematic, control flow diagram, data point, alarm, control sequence, function, programming code, and references, each with unique attributes and formats. A single-duct variable air volume (VAV) multi-zone system case study showed how to modularize and generate the BCK representation for each control module using control variables ontology analysis.

Also, Martín-Gómez et al. [54] investigated the design, construction, and performance of a Peltier cell-based thermoelectric cooling heating unit (TCHU) prototype for domestic air conditioning. The prefabricated, modular, and autonomous TCHU can be inserted into the building exterior as a facade element. Depending on the season, it might be a heat pump or HVAC system. The study covered the TCHU prototype's theoretical design, components, control system, testing procedures, and findings. It included benefits, drawbacks, and system upgrades. The study found the TCHU system to be a practical and unique building air conditioning solution. Still, it needs optimization to reduce power consumption, improve insulation, and better aesthetic integration.

Li et al. [44], the final study in this category, examined the current practices, challenges, and opportunities of piping prefabrication in China using semi-structured interviews, case studies, site visits, and online questionnaires. The study found that piping prefabrication feasibility depends on the piping system, connection style, and project type. The study also identified piping prefabrication's primary problems and barriers, including low design standardization, absence of favorable policy, economies of scale, low-skilled workers, and fittings and valve availability. The study proposed that MEP contractors use modular and off-site construction (MOC) to prefabricate pipework in four phases to improve their construction. The study also examined how manufacturers, distributors, designers, and contractors collaborate in piping prefabrication.

In modular construction, the primary skills needed are typically within the production plant, with only minimal labor required for the installation procedure [55]. However, the successful integration of building services in modular construction necessitates the presence of a skilled workforce. The issue of skills shortage in the construction industry necessitates implementing more effective manufacturing and automation techniques [56]. In this regard, universities and industry can collaborate to play a crucial role in delivering training and fostering the acquisition of essential skills [55].

- **Recent advances**

According to Liew et al.'s study [48], long-span modules can increase open space and flexibility in floor layout, decrease the number of joints and columns, and speed up and improve the efficiency of modular construction. Fast-installed joining procedures were created to minimize internal finishes and on-site work damage. Various facets of modular construction, including robustness, tolerance, automation, global modeling, fire safety, and robustness, were explored along with their design problems and solutions.

In addition, Martinez et al. [50] advocated rebuilding industrial construction machines utilizing simulation, time studies, and cost-benefit analysis. The process optimized design parameters to increase machinery performance and cost. The study also redesigned wood framing machinery support tables, which secure and drag the frame during manufacture. Reducing track length and altering dragging logic were recommended to improve panel length adaptability and minimize space and expense. The wood framing machine prototype and operational data created a simulation model. The model simulates track length and dragging scenarios to calculate total duration, operational time, production pace, productivity growth, and system utilization.

Meanwhile, Guo et al. [49] developed an automated method to predict MEP module geometric parameters using 3D laser scanning and BIM. The study pre-processed, registered, and extracted MEP module point cloud data from a terrestrial laser scanner. MEP element dimensions and placements were checked against the point cloud data and the as-designed BIM model.

- **Current and future directions**

According to Lopez et al. [43], Australian builders and suppliers face challenges and opportunities for off-site prefabrication of timber components and MEP services. The study compared and analyzed interview data from four builders and four suppliers. They shared their knowledge of off-site prefabrication coordination, integration, and management. The study also addressed quality assurance, commercial arrangements, technological assistance, numerous supply agreements, and design coordination as barriers to off-site prefabrication. The study also suggested enhancing builder–supplier collaboration and off-site prefabricated component design and delivery.

Similarly, Suárez et al. [52] proposed a computational method to determine the optimal modularity of residential MEP systems in remote settlements like Nunavik, northern Quebec, Canada. The framework considers system installation cost, local employment creation, module characteristics (dimensions, direction changes, etc.) on modularization, collision limits during assembly, and remote communities. Configurations were evaluated using fuzzy logic models and the NSGA-II algorithm to find non-dominated solutions. After applying the framework to a heat transfer fluid distribution system in a typical Nunavik housing unit, installation costs drop by 81.9%, and local job creation rises by 23.4 local work hours. Relatedly, Baek et al. [47] designed a cost-effective prefabricated MEP rack (PMR) structural framework. PMR multi-trade prefabrication unifies MEP elements into one unit. The project pilot tested five PMR structural framing methods to determine their channel material and labor requirements. Types vary by supporting intervals, duct placements, and upper frame. The study adjusted the supporting interval, moved the duct outside, and removed the upper framing to test PMR structural frame efficiency. Economic and productivity studies showed that removing the upper framing method worked best when securing the coordination period. Another cost-effective design option was modifying supporting intervals.

Palani and Karatas [3] recently evaluated experimental and computational methods for quantifying EIFS prefab wall panel thermal performance. The study investigates the idea that both approaches can accurately assess EIFS prefab wall panel thermal performance in different climates and produce similar results. The investigation disproved the theory and revealed significant procedure differences. Experimental test analysis using an environmental chamber showed higher thermal resistance values for EIFS prefab wall panels than THERM software modeling. The difference is 11.5% hot and 22.2% cold. According to the study, the margin of error of the two-dimensional simulation model and experiment sensors caused the discrepancy. The study also showed the financial effects of the disparity on a typical US hospital building prototype. Using EnergyPlus software to simulate the annual energy consumption and cost savings of a Denver, Colorado, hospital building with EIFS prefabricated wall panels as the external wall insulation system, experimental thermal resistance values instead of computational ones can save $396,000 over 20 years due to lower construction costs, HVAC system selection, and utility bills. Figure 9 highlights the current and future directions for integrating building services in modular construction.

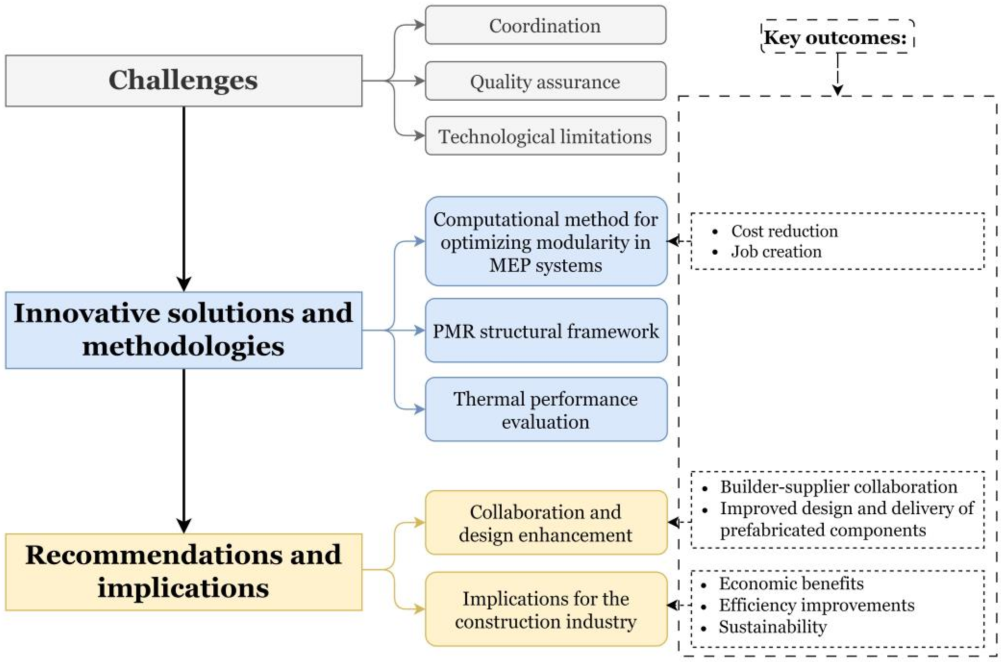

Figure 9. Overview of current and future directions of research theme.

The most apparent benefits of modular construction, which successfully supports sustainable construction, are better productivity and quality, cost savings, increased safety, improved product control and quality, and less harmful environmental effects [57,58]. By incorporating these cutting-edge technologies and methodologies (see Figure 9), modular construction can effectively tackle its inherent difficulties and offer a cost advantage across the lifecycle compared to conventional construction techniques. This is particularly noteworthy, considering the post-assembly service costs, which can often exceed the initial construction costs. This study's findings indicate that implementing a well-designed modular building can result in substantial cost reductions in the maintenance and operations of the integrated building services, enhancing efficiency and sustainability. Nevertheless, definitive and robust cost assessment studies, such as life cycle cost assessments, are required to substantiate the economic superiority of modular construction over equivalent conventional construction [57].

4. Discussion

4.1. Advancements and Integration of Technology in Modular Construction

Since the Industrial Revolution, mass production has dramatically benefited the construction industry [45]. Standardizing components like bricks, beams, and windows enabled the mass production of building materials, significantly reducing prices and expediting the construction process. Modular construction uses fully fitted, room-sized volumetric components placed on-site, and the primary benefits include improved quality and precision, quick on-site installation, and cost-effective production of many units [59]. Modular construction includes prefabrication, mechanization, automation, robotics, and reproduction [60]. As construction elements progress from materials to components, then to modules and complete units, prefabrication complexity and component integration increase while on-site work declines [60,61]. This study has extensively reviewed research on building service integration in modular construction. The temporal publication trend demonstrates a rising corpus of research in this area, highlighting the growing recognition of modular construction's ability to improve building industry efficiency. The study suggests a shift toward building techniques that are more technologically advanced and sustainable. Emerging technologies such as artificial intelligence (AI) and machine learning (ML) can significantly enhance construction processes and contribute to the development of sustainable communities [46]. The integration of developing technology into different aspects of building design, construction, and operation has been the subject of several studies.

Recent studies have specifically examined the application of emerging technologies in modular construction. Zhou et al. [62] identified three primary challenges: inefficient data capture methods, ineffective progress supervision, and lack of automatic decision support in integrating BIM and related techniques in MIC on-site assembly services. The study presented an Internet of Things-enabled intelligent BIM platform (SBIMP), which integrates the Internet of Things (IoT), BIM technologies, and computing techniques to facilitate real-time information capture, processing, display, and sharing among various stakeholders to support their decision-making process during the on-site assembly process. Similarly, Zhai et al. [63] present an IoT-enabled BIM platform (IBIMP) that facilitates the delivery of modular integrated construction (MiC) projects by enabling real-time information collection, autonomous decision support, and emergence alarm. The study presented service tools such as traceability and visibility tools, dynamic decision optimization tools, and automatic order dispatching tools to support stakeholders and managers in supervising and controlling the entire construction process and facilitating coordination among independent parties. Meanwhile, Iacovidou et al.'s [64] study focused on the reuse and waste reduction of modular components by collecting and storing components' life cycle information. The study showed that radio frequency identification (RFID)-BIM employment can enhance interoperability between stakeholders in the construction value chain while improving project lifecycle management monitoring. RFID-BIM can be particularly attractive in promoting innovation and unlocking multi-dimensional value. Incorporating cutting-edge technologies such as AI, ML, IoT, and BIM in modular construction can expedite the exchange of information in real-time, enhance decision-making, and foster collaboration among stakeholders. This integration is vital for improving the integration of building services in modular construction.

4.2. Potential Influence of Recent Technologies on Building Services Integration in Modular Construction

The construction sequence of a modular unit consists of six phases: structural frame manufacturing, MEP installation, installation of interior and exterior finishes, module transportation (to the site), module lifting, and installation at the site [48]. However, specific modular construction projects incorporate both off-site and on-site building services. Combining off-site and on-site construction demands careful planning and coordination among the design, manufacturing, and on-site construction teams. Hong Kong Housing Society proposes constructing a 25-story subsidized-for-sale house on Hung Ping Road in Hung Shui Kiu using modular integrated construction. The project will consist of 300 one- to three-bedroom units, ranging from 360 to 633 square feet [65]. Figure 10 shows the integration of building services at the project's mock-up site. As shown in Figure 10a, a well-defined framework for tackling these integration challenges involves clearly distinguishing between tasks completed off-site and on-site.

Modular construction is better quality, involves less labor, and emits less carbon [66]. As all pre-engineered volumetric frames in a modular construction system are built within tight tolerance levels in a controlled factory setting, supplied to the project's location on a 'just-in-time' basis, and assembled into complete building systems [67], the integration of building services such as fluid transportation, heating, ventilation, and related systems in MEP modules is paramount. MEP modules are components of modular construction consisting of cable trays, ducts, and pipes [49]. Similarly, piping is a network of pipes used to transport fluids from one point to another; plumbing is the most common type of piping [44]. The primary objective of building services technology is to create a conducive indoor environment for buildings while maximizing energy efficiency [4]. Similarly, the integration of BIM in buildings has become increasingly important. Modular building technologies have proven effective and desirable, allowing for a streamlined process from planning and design to manufacturing and construction [68].

(a) HVAC systems (b) Onsite and offsite services installation

(c) MiC unit (d) MiC mock-up site

Figure 10. Case study of building services integration in modular construction.

Other potential impacts of emerging technologies in integrating building services for modular construction include predictive maintenance, assembly precision improvement, real-time quality assurance, and control, simplified on-site logistics, and integration. IoT technology can help intelligently maintain building services after installation. HVAC, plumbing, and electrical systems can be monitored to provide maintenance personnel with performance data and early alerts of potential concerns. AI can assess this data and predict maintenance needs, enabling a proactive maintenance model. Similarly, AI can also improve assembly line efficiency by reacting to changes in production schedules in real time. Additionally, IoT devices can monitor material quality and construction integrity throughout the manufacturing process. Sensors can detect structural flaws and material faults before modules are sent from the factory. Continuously feeding these data into AI systems for quick analysis and response increases quality control. Meanwhile, AI and IoT could improve on-site modular unit transport and assembly logistics.

5. Conclusions and Future Studies

Despite technological advancements and methods, difficulties exist, especially when standardizing procedures and modifying building services to fit installations. Innovation is required in integrating MEP systems since the intricacy of coordinating activities both on and off-site continues to be a significant problem. In addition, the study reveals a mismatch between modular building approaches' theoretical potential and real-world implementation, underscoring the necessity for empirical research on life cycle analysis and long-term performance. Additionally, new research directions are being opened by developing intelligent building services and digital technologies like BIM, IoT, and AI. These technologies could fill the gap between the prefabrication procedures of modular construction and the dynamic needs of building services integration. In the same vein, establishing industry-wide standards requires a comprehensive approach. This strategy would span the complete process from design to construction and operation, ensuring that the modular components are economically efficient and environmentally friendly and adhere to the necessary performance criteria. Given that technological needs and units of modular construction may vary depending on their functions, an overview of the relationship between function, design, and the production of prefabricated modules in building services integration can be found by readers in refs. [69–71].

The study presents a multifaceted approach to building services engineering that is increasingly impacted by integrating cutting-edge technologies and methods like AI, IoT, BIM, and modular construction. The current study reflects a continuous tendency toward efficiency and mass production in buildings and draws from earlier historical progression and standardization studies. This study extends the knowledge on the evolution of modular construction by describing how these systems integrate state-of-the-art technical frameworks, increasing accuracy and decreasing on-site labor—a substantial advancement over traditional approaches.

Future studies could focus on creating a coherent framework covering modular construction design, construction, and operation phases and integrating building services using Delphi or case study analysis methodologies. While the former will utilize expert panels from academia and industry to develop consensus on sustainable and efficient modular construction, the latter would involve detailed documentation and analysis of several projects on building services integration in modular construction over time. Also, comparative performance studies could be explored to set up parallel studies comparing modular and traditional building methods to gather data on efficiency, sustainability, and life cycle costs.

Guidelines that direct modular building toward greater levels of sustainability and efficiency should be developed through collaboration between academia and industry. This study's limitations include the potential bias caused by the selection criteria, the potential omission of relevant studies not indexed in the Scopus database or via the Research Rabbit App, and the exclusion of gray literature. Furthermore, given how quickly technology is developing in the construction industry, it might be necessary for future studies to describe the most recent practices completely.

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