Journal of Building Engineering 73 (2023) 106725

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

A systematic literature review on modern methods of construction in building: An integrated approach using machine learning

Antonio J. Sánchez-Garrido [a,*], Ignacio J. Navarro [a], José García [b], Víctor Yepes [c]

[a] Dept. of Construction Engineering, Universitat Politècnica de València, 46022, Valencia, Spain
[b] School of Construction and Transportation Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, 2362807, Chile
[c] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022, Valencia, Spain

ARTICLE INFO

Keywords:
Modern methods of construction
Industrialized buildings
Emerging technologies
Construction industry
Machine learning
Systematic literature review

ABSTRACT

The concerns surrounding sustainability, alternative energies, and lifestyle changes due to the pandemic have resulted in a surge in the manufacturing of buildings utilizing Modern Methods of Construction (MMC), particularly in housing. These methods involve using new technologies as smart building alternatives to traditional construction. Against the backdrop of Industry 4.0, there is an urgent need for a systematic literature review of MMCs in building construction to classify them, detect trends and gaps, and outline future research areas. This study analyzed 633 publications from 1975 to 2022 and grouped them into six thematic clusters and 18 subcategories, using a novel mixed methodology incorporating natural language processing (NLP) analysis. The qualitative analysis of the literature indicates that research in the field is dominated by tools and technologies integrated into Construction 4.0 and the industry's management aspects. However, this review also highlights several gaps in research, including the need for more application of MMC to building retrofitting and the need for approaches to improve the built environment through the new paradigm of regenerative design. The high-level mapping and characterization of the bibliographic corpus's conceptual structure and the classical evaluation process based on systematic literature review (SLR) have provided a more profound and rigorous state-of-the-art understanding.

1. Introduction

The construction industry is crucial in driving economic growth in many countries. While it experienced substantial growth between 2014 and 2018 compared to other industries, such as industrial and services, the sector was impacted by the Covid-19 pandemic in 2020, causing a slowdown. Currently, the industry is in recovery, as reflected in the real estate market's performance. With high savings rates due to reduced demand over the past two years, real estate investment has become an attractive option for funds, especially in the context of rising inflation in the European Union. The impact of the pandemic has prompted discussions and reevaluations of architecture, particularly in the residential sector [1]. Covid-19 has increased demand for high-quality housing [2], especially single-family homes, with faster lead times and a growing global recognition of the importance of environmentally friendly and sustainable construction and demolition practices [3]. As a result, the qualifications and standards for construction, particularly in housing, have become more rigorous to meet the demands of modern society.

---

* Corresponding author.
E-mail addresses: ajsangar@doctor.upv.es (A.J. Sánchez-Garrido), ignamar1@cam.upv.es (I.J. Navarro), jose.garcia@pucv.cl (J. García), vyepesp@cst.upv.es (V. Yepes).

https://doi.org/10.1016/j.jobe.2023.106725
Received 8 March 2023; Received in revised form 19 April 2023; Accepted 30 April 2023

Industry 4.0 is rapidly transforming the construction sector, with one of the most advanced proposals being the implementation of technological solutions to automate construction processes and improve the supply chain [4]. In this context, Modern Construction Methods (MMCs) are gaining popularity as an alternative to traditional construction. The advancements in artificial intelligence (AI) [5], the adoption of collaborative methodologies such as Building Information Modeling (BIM) [6], and the focus on sustainability have encouraged more and more real estate developers to embrace this construction model. It is seen as the future of a sector that has yet to see much change in recent decades, especially residential construction.

MMC is a broad concept first used by the UK government to describe innovations in housing construction. It encompasses a range of technologies, many of which are off-site construction (OSC) methods that move work to the manufacturing site [7]. This encompasses integrated module construction, pre-fabrication, pre-assembly, panelized systems, industrialized construction, off-site production or manufacturing, and various on-site and hybrid construction methods [8]. MMC allows the building to be primarily defined in the design phase, as more than 90% of the building activity is performed off-site [9]. This leads to the early resolution of potential problems and minimizes improvisation during construction. The industrialization of construction processes enables the incorporation of automation, resulting in efficiency and meeting deadlines. This approach also emphasizes the specialization and professionalization of construction agents, leading to higher quality standards.

MMCs are transforming how buildings are constructed to be faster, safer, cost-effective, and more efficient. During the Covid-19 pandemic, the world saw MMCs in action as two emergency hospitals were built in Wuhan, China, in just 12 days [10]. Research has shown that industrialized systems, prefabrication, and mobile factories with on-site component production can save up to 50% in construction time and 30% in costs, all while involving the future user in the process [11]. The drive to increase resource productivity, improve quality and safety, enhance business efficiency, meet customer needs, reduce environmental impact, promote sustainability, and control delivery times drives innovation in the construction industry [12]. In recent years, MMCs have rapidly gained popularity in the real estate sector to meet the demand for fast, simple, and environmentally-friendly housing. While MMCs have spread globally, the number of active countries still needs to grow, and production is uneven among them. Within Europe, countries such as the UK (7% of total housing), Germany and France (9−10%), the Netherlands (50%), and parts of Scandinavia have a well-established MMC sector [13]. Sweden and Japan [14] are at the forefront of MMC innovation.

The last decade has seen various research strategies undertake these methods. These studies have analyzed various aspects, from limitations to benefits, such as the impact on the supply chain [15], cost and lead times [16], reduction of occupational risks [17], design issues [18], sustainability [19], and productivity [20]. Some researchers have focused on specific countries [14,21] or limited their study to a specific method [22,23] or stage of the construction process [24]. However, the literature on MMCs needs to be thoroughly reviewed with a comprehensive and unbiased approach, leading to a lack of a complete and accurate classification of these modern construction techniques. To the authors' knowledge, there is no complete, accurate, and unified classification in MMC. The term MMC is sometimes used interchangeably with other terms [25] such as off-site manufacturing (OSM) or industrialized building system (IBS), leading to confusion.

Recent reviews have been on different topics related toindustrialized construction, with issues such as BIM [6], digital technology [26] or robotic [27], whose research has a more specific purpose in addressing the sector's problems. However, there needs to be more studies from a broader perspective covering the majority of MMCs applied to the building, particularly the residential typology where they are most recurrently used. This investigation aims to gather and consolidate fragmented studies on the topic, providing a comprehensive overview of MMCs and facilitating the work of future researchers. Previous studies have focused on highlighting the advances in new technologies [28,29] in response to the changing requirements of the OSC. However, several knowledge gaps are detected that invite us to deepen and critically comment on the trends in MMCs, especially those promising for the future of building not only in new construction but also in the built environment through rehabilitation and regenerative design.

The focus of this study is to address three research questions through a systematic literature review (SLR). First: What MMC-based systems have been used in building construction in recent times? Second: On what specific construction-related problems have these MMCs been applied? Third: What are the gaps and the future research trends in the existing MMC literature?

The specific objectives of the study are (1) to categorize and analyze the various types of MMCs used in building construction and their recent evolution; (2) to develop a novel, systematic, and comprehensive methodology for scientific mapping literature on MMCs using bibliometric parameters; (3) to explore the main topics, areas of application, and current trends in MMC-based construction; and (4) to identify existing gaps and make recommendations for future research in MMCs and its application mainly to residential buildings.

Consequently, this research is the first to perform a comprehensive, critical, and more extensive analysis of Modern Construction Methods applied to the building sector. The study is structured to achieve these objectives through a sequential and comprehensive approach by following step-by-step the following sections.

2. Overview of MMCs in the building industry

2.1. A brief historical review of industrialized construction

The 21st-century construction industry offers the possibility of creating high-quality buildings at proportional costs, surpassing traditional architecture's low productivity and insecure labor conditions. Industrialization, or prefabrication, involves the production of building components in a factory to form complete units with a refined finish, which are then transported to the construction site. Although there is growing interest in these MMC, their origins can be traced back to the 17th century.

2.1.1. Origins of MMCs

The earliest recorded instance of prefabricated houses was in 1624, when they were manufactured in England for shipment to Cape Ann in Massachusetts [22]. The development of industrialized construction is credited to the U.S. in the early 19th century when traditional timber beams and piers were replaced with a frame made of multiple slats of smaller sections, which required less skilled labor and was easier to assemble. This system, known as the "Balloon Frame," gradually transitioned from traditional European construction methods, and it gained popularity in Chicago around 1833 [30]. Today, it is widely used as "Light Steel Framing" (LSF), which consists of skeletons made of thin, cold-formed, galvanized metal profiles. In the U.K., prefabricated wooden shelters with metal enclosures were produced and shipped to the colonies in New South Wales, Australia, where they were known as "Colonial Portable Cottages" [31]. These units were designed to be lightweight and straightforward to transport. Later, similar units were sent to Africa, where they were used to build shelters in Sierra Leone and the Eastern Cape [32].

The 1851 Great London World's Fair marked a turning point in industrial construction with the unveiling of the Crystal Palace. Designed by Joseph Paxton, it was the first building of its size to feature a cast-iron frame and glass panels, and its quick assembly using inexpensive materials made it a marvel of its time [22]. In 1908, the Sears Roebuck & CO company revolutionized the single-family housing industry by selling millions of prefabricated "Kit Houses" in the US, constructed with wood framing and siding that reduced building time by up to 40% [33]. From 1911 to 1917, renowned architect Frank Lloyd Wright introduced the "American System-built Houses" for the Richards Company, utilizing an industrialized production system for building components with the ability to add on or modify easily.

2.1.2. The first half of the 20th century

Le Corbusier, a highly influential architect of the 20th century, received criticism for his view of housing as a machine for living. In 1914, he patented the "Maison Dom-ino" structural framework of slabs and pillars, also known as the "Brevet 2.26 × 2.26" grid system, which served as the blueprint for projects such as the Swiss Pavilion of the University City in Paris in 1932 [34]. In 1930, the General Electric and American Houses companies introduced the "General Houses" and "American Motohome" in the US, which utilized steel load-bearing panels and thermal insulation core, though they still required specialized assembly. Around the same time, the "House-on-Wheels," the first example of transportable modular housing, became famous thanks to its use in permanent caravan parks [35]. Richard Buckminster Fuller's "Dymaxion House" of 1930, later improved as the "Wichita House" in 1945, was a semi-assembled aluminum system with hanging structures like bicycle spokes, struts for roof support, and a central stainless steel post [30]. This design, which emphasized natural ventilation and efficient use of materials, was ahead of its time and established Fuller as a pioneer in sustainable construction.

Architect Walter Gropius also made significant contributions to the production of single-family housing. In 1941, he introduced the "Packaged Houses," which used dry construction with modular wood panels that could be assembled vertically and horizontally with metal L, T, and X-shaped plates [36]. The "Case Study House" program, from 1945 to 1966, emerged in response to the massive demand for housing in the US following World War II [31]. Thirty-six prototypes of industrialized architecture were designed by notable architects of the time, using prefabricated materials and cutting-edge technologies. One of the most famous of these was the Charles and Ray Eames-designed Case Study House No. 8, which was built in 1949 at a low cost and in just 90 h [30]. In 1947, the "AIROH Houses" was introduced in the US, featuring aluminum bungalows with an innovative construction using extruded profile structure panels and aluminum enclosures filled with cellular concrete coated internally with plaster. The houses comprised four sections, each of which could be assembled in 12 min, excluding the traditional wooden floor construction [35].

2.1.3. The second half of the 20th century

In 1949, Jean Prouvé created 14 prefabricated houses in Maisons Meudon, Paris, for the French Ministry of Reconstruction. The houses were made of a metal frame with a central portico and enclosures made of wood or metal sandwich panels. With the "Metropol" system, the house was largely pre-constructed, ready to be installed on load-bearing walls when it arrived at the building site [32]. In 1954, Prouvé built his own home in Nancy using recycled materials from an old factory. In 1955, the sturdier "Mobile House," a transportable three-dimensional modular home, began production in the U.S. The "Mobile House," a three-dimensional modular home that could be transported on a truck, required a crane for permanent installation on-site. One of this era's most notable residential projects was Moshe Safdie's "Habitat 67," built in Montreal for the 1967 Olympic Games. This project was unique for its 354 stacked precast concrete modules with dimensions of 5.3 × 3.0 × 11.5 m [34]. In 1969, the German company Okai introduced the "Metastadt" system, consisting of lightweight prefabricated modules made of bolted steel profiles with dimensions of 4.20 × 4.20 × 3.60 m. The same year, Barton Myers Associates in Canada developed the "Stelco House" system, a three-dimensional system with dimensions of 3.60 × 3.60 × 3.60 m [35]. The system came with an assembly guide that allowed unskilled personnel to assemble or disassemble it for reuse quickly, but it was never commercialized.

In 1970, the "Manufactured Home" was introduced in Florida due to rising transportation costs. The homes were factory-assembled and measured 2.44 × 12.00 m. In 1971, the "Moduli 225" system, a wooden construction measuring 2.25 × 2.25 × 2.25 m, was developed by Gullichsen and Pallasmaa [32]. It was innovative to use a steel-based spatial joint to connect six pieces. The iconic "Nakagin Capsule Tower" in Tokyo, completed in 1972, was a remarkable example of industrialized construction [36]. Designed by architect Kisho Kurokawa, it consisted of precast concrete cells containing 140 apartments, which arrived fully assembled at the construction site. In 1975, Paul Rudolph improved upon the "Manufactured Home" with his "Modular Homes." These three-dimensional, transportable single-family houses were designed similarly to shipping containers. They could be expanded or stacked by joining modules measuring between 2.50 and 3.50 m in width and 6.00–12.00 m in length, with an approximate weight of 200 kg/m^2 [35]. Modular construction remained limited in scope until the advent of computer technology and computer-aided design programs in the 1980s. In recent decades, the sophistication of industrialized construction has increased with the advancement of MMCs and new technologies.

2.2. Definition and terminology related to MMCs

Modern Methods of Construction (MMC) encompasses a wide range of advanced construction techniques and systems, both off-site and on-site that offer an alternative to traditional construction, particularly in the housing sector. MMC has been referred to by various names, including precision-manufactured, pre-manufactured, modular, prefabricated, volumetric, hybrid, industrialized building system (IBS), and off-site manufacturing (OSM), among others. However, MMC encompasses innovative techniques that involve either on-site fabrication or assembly of certain elements. The UK government first introduced the term to address high demand, shortage of skilled labor, and high construction costs in the housing sector [6]. In literature, MMC is often related to different globally recognized terms [37], with OSM or IBS particularly prominent in Australia and Malaysia. Although off-site construction originated in the UK after World War II, it began to diversify globally in the 1970s, particularly in response to the need for mass housing in rapidly growing cities such as Hong Kong and Singapore. Table 1 summarizes the different globally recognized terminologies for non-traditional construction methods across different countries.

2.3. Revising classification issues

For two decades, there has been an ongoing debate about alternative construction methods without a universally agreed-upon classification. In 2003, the Housing Corporation released a five-tier classification of dwelling construction systems based on their criteria, including off-site manufactured systems like volumetric, panelized, hybridized, subassemblies or components, and non-off-site manufactured Modern Methods of Construction (MMC) [38]. Multiple attempts have been made to categorize modern construction methods and techniques, with the most relevant and accepted definitions compiled in Table 2. The commercial classification of MMC established by the Housing Corporation has remained unchallenged since its introduction [39]. Many MMCs today are funded by Housing Corporation grants or located on English Partnership land [40]. Other proposals for classification tend to define MMCs in terms of materials, processes, or systems, which may seem more straightforward.

The limitations of the existing classifications of MMC have contributed to confusion in the field. MMC is often misconstrued with other similar terms, leading to varying definitions in different countries. Additionally, the absence of a standard classification adds to the ambiguity. For instance, not all MMCs fall under the umbrella of OSM, and hybrid methods, where off-site and on-site construction coexist, make it challenging to categorize them strictly as off-site production. The classifications presented in Table 2 are limited to basic, one-dimensional categories, overlooking the interconnections between the various methods and their hierarchical relationships.

Given the advancements brought on by Industry 4.0 in the construction sector, there is a need for a more comprehensive classification system for the constantly evolving methods of Modern Methods of Construction (MMC). This research offers a proposed classification of MMC as a conceptual mindmap to address this issue (Fig. 1). This new classification aims to organize the fragmented categories, create a hierarchy among the various existing MMCs, and accommodate new additions dynamically.

3. Research method

This research aims to thoroughly study the latest advancements and market opportunities in using MMCs in the building industry. A unique hybrid approach has been employed that blends Machine Learning (ML) techniques with expert knowledge for a more comprehensive and accurate analysis. This method, referred to as "mixed review," combines natural language processing (NLP) analysis and a systematic literature review (SLR) to achieve a thorough understanding of both the domain knowledge and current research trends. By combining the strengths of both NLP and SLR methods, the research eliminates subjective interpretations and provides a balanced and rigorous comprehension of the field [57]. The results of this research will provide a comprehensive, high-level

Table 1
Related terms around the world to refer to non-conventional construction methods.

Terminology	Acronym	Countries
Modern Methods of Construction	MMC	UK, Spain
Off-Site Manufacturing	OSM	Australia
Industrialized Building System	ISB	Malaysia, Thailand
Prefabrication, Preassembly, Modularization, Offsite Fabrication	PPMOF	US
Off-Site Construction	OSC	China
Prefabricated Prefinished Volumetric Construction	PPVC	Singapore
Modular Integrated Construction	MiC	Hong Kong
Off-Site Production	OSP	Germany
Industrialized Construction	–	Sweden, Finland, Denmark
Industrialized Housing	–	Netherland
Prefabricated Housing	–	Japan, Philippines
Modular Construction	–	Canada

Table 2
Evolution of the classifications proposed to define industrialized construction. Adapted and expanded from Ref. [41].

Definition/Author(s)/Year	Categories	Ref.
Modular housing systems. Majzub (1977)	(1) Panel system; (2) Box system; (3) Frame system	[42]
Building system classification. Badir et al. (1998)	(1) Conventional column-beam-slab frame system; (2) Cast in-situ system with steel or aluminum as formwork; (3) Prefabricated (panel, block and frame) system; (4) Composition system	[43]
Industrialized and Automated Building System (classification A). Warszawski (1999)	(1) Timber; (2) Steel; (3) Cast in-situ concrete; (4) Precast concrete	[44]
Industrialized and Automated Building System (classification B). Warszawski (1999)	(1) Linear; (2) Skeleton; (3) Planar; (4) Planar system; (5) Three-dimensional box systems	[44]
Fully prefabricated construction methods. Badir et al. (2002)	(1) Precast Concrete (on site & off site); (2) Load Bearing Block (off site); (3) Sandwich Panel (off site); (4) Steel Frame (off site)	[45]
Off-Site Construction (OSC) classification. Gibb & Isaac (2003)	(1) Modular Building; (2) Volumetric pre-assembly; (3) Non-Volumetric pre-assembly; (4) Components manufacture & subassembly	[46]
Industrial Building System (IBS) classification (CIDB−Malaysia). Shaari et al. (2003)	(1) Pre-cast concrete framing; (2) Panel and box systems; (3) Steel formwork systems; (4) Steel framing systems; (5) Prefabricated timber framing system; (6) Block work system	[47]
Modern Methods of Construction (MMC) classification. Gibb & Pendiebury (2005)	(1) Volumetric; (2) Panellized; (3) Hybrid; (4) Subassemblies and components; (5) Non-off-site-Modern Methods of Construction	[39]
Industrial Building System (IBS) classification (UTM−Malaysia). Rahman & Omar (2006)	(1) Pre-cast concrete-framed building; (2) Pre-cast concrete wall system; (3) Reinforced concrete building with pre-cast concrete slab; (4) Steel formwork system; (5) Steel-framed building and roof trusses	[48]
Industrial Building System (IBS) classification. Richard (2007)	(1) Site intense kit part; (2) Factory made module; (3) Hybrid	[49]
Off-Site Manufacturing (OSM) classification. Abosoad (2009)	(1) Volumetric system; (2) Panellized system; (3) Hybrid system; (4) Sub-assemblies and component system; (5) Modular system	[50]
Offsite Construction Techniques Lu (2009)	(1) Offsite preassembly; (2) Hybrid system; (3) Panellized system; (4) Modular building	[51]
Blismas and Wakefield (2009)	(1) Non-volumetric preassembly; (2) Volumetric pre-assembly; (3) Modular building	[52]
Industrial Building System (IBS) classification. CIDB (2011)	(1) Pre-cast concrete framing, panel and box systems; (2) Steel formwork systems; (3) Prefabricated timber framing system; (4) Steel framing systems; (5) Block work system; (6) Innovative system	[53]
Modular construction typologies. Doran & Giannakis (2011)	(1) Pure modular; (2) Hybrid modular; (3) On-site modular	[54]
Modern methods and materials in construction. Mesároš & Mandičák (2015)	(1) Frame system; (2) Panel system; (3) Modular system	[55]
Types of Modern Methods of Construction (MMC). Khan & Khan, (2019)	(1) Precast Flat Panel System; (2) 3D Volumetric Modules; (3) Flat Slab Construction; (4) Precast Concrete Foundation; (5) Twin Wall Technology; (6) Concrete Formwork Insulation; (7) Precast Cladding Panels; (8) Concrete Wall and Floors; (9) Prefab Bathroom Pods; (10) “Mivan” Construction (aluminium formwork)	[56]

mapping and characterization of the MMCs applied in the building sector.

3.1. NLP methodology

This section describes the methodology for selecting articles and creating visualizations. Due to the recent and fragmented nature of the topic, it was not feasible to perform a direct Scopus search of MMC. Therefore, an iterative approach based on topic modeling was used to compile a list of articles. Fig. 2 shows the flowchart of the methodology based on Natural Language Processing (NLP). Table 3 details a list of the main topic modeling methods used in the literature. Fig. 3 details the methodology used in the review process.

Initially, a Scopus search was conducted using keywords related to Modern Methods of Construction. The results of this search were processed using Natural Language Processing (NLP) to identify the key topics related to modern construction methods. Bidirectional Encoder Representations from Transformers (BERT) [58] were used to encode the words that make up these topics, effectively capturing the semantic relationships between different concepts. Next, a dimensionality reduction technique was used to simplify the dataset. Numerous dimensionality reduction techniques exist, for example, PCA [59], which considers a linearity condition for its transformation. For this case, due to the complexity of the dataset, the non-linear relationships, as suggested by previous studies [60], and the Uniform Manifold Approximation and Projection for dimension reduction (UMAP) [61] were used. Also, finally suggested by Ref. [62], the clustering process was performed using the Hierarchical Clustering and Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) method [63].

Once the initial selection of articles is made, the selected papers undergo further analysis through various visualizations to gather statistics on the author network, citation analysis, and central concepts. Thematic analysis is then performed using Latent Dirichlet Allocation (LDA) [64]. This analysis identifies relevant topics and leads to a final selection of papers through a manual citation process based on a Systematic Literature Review (SLR). This process includes two types of analysis: a bigram analysis and a traditional analysis

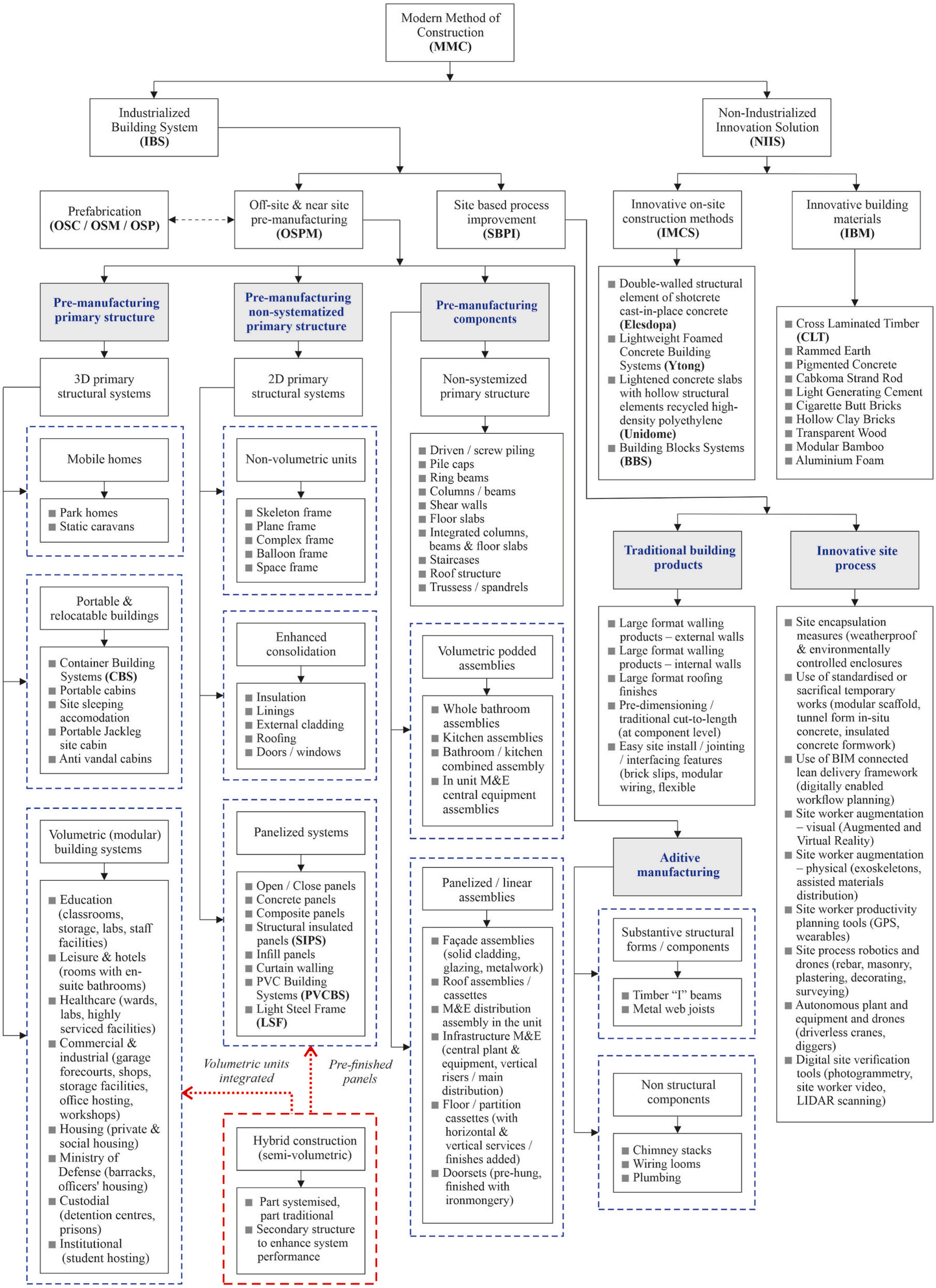


Fig. 1. Mind map with the new classification proposal for MMC in building.

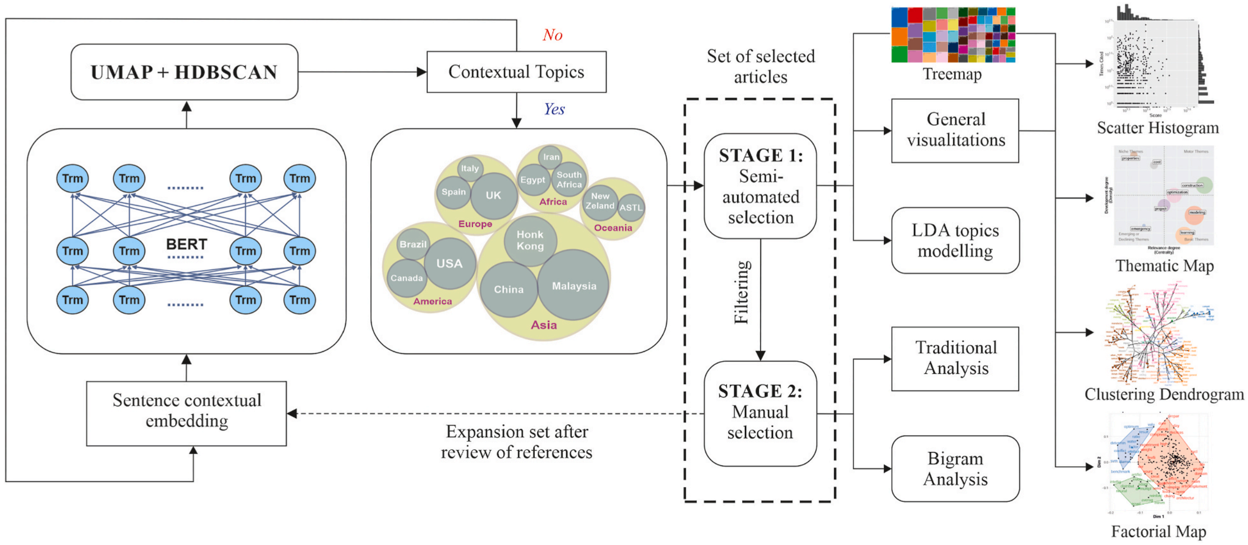


Fig. 2. NLP methodology flow chart.

Table 3
Topic modeling algorithms.

	Ref.
Latent Dirichlet Allotation	Blei et al. [64]
Latent Semantic Analysis	Landauer et al. [68]
Parallel Latent Dirichlet Allocation	Wang et al. [69]
Non-Negative Matrix Factorization	Lee and Seung [70]
Pachinko Allocation Model	Li and McCallum [71]
Bert + Clustering	Grootendorst [62]

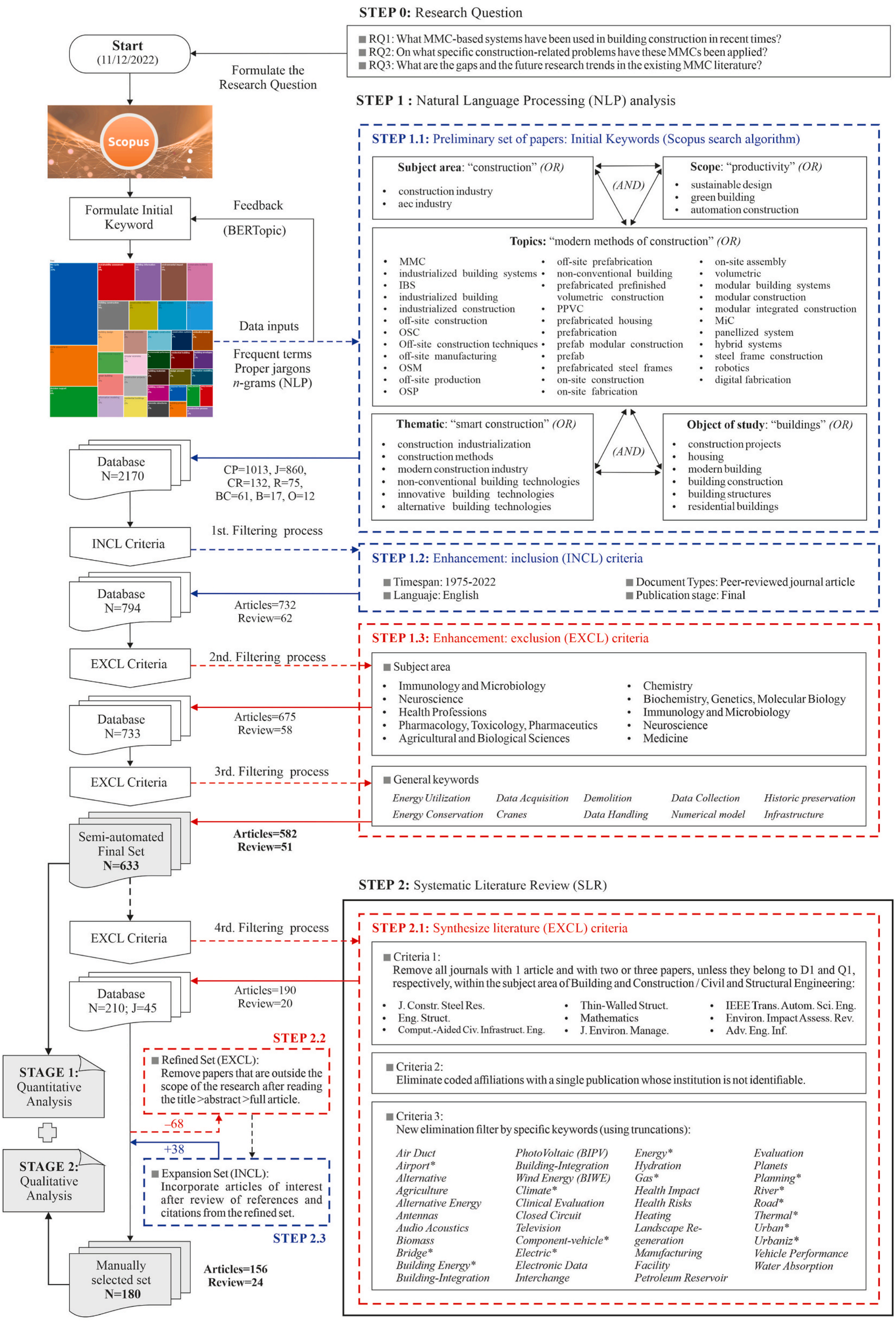
of the sample papers. This process of analyzing topics and refining the search was repeated until the final selection of articles was made.

This analysis aims to examine the frequency distribution of bigrams, which are pairs of contiguous words, in the abstracts under study. The R-bibliometrix program [65] was used to conduct the analysis. Five specific visualizations were applied. The Treemap determines the frequency of the primary bigrams in each theme. Scatter and distribution histograms represent the relevance score and citation indexes, respectively. The thematic map combines the concepts of internal associations (density) and external associations (centrality) [66,67]. Four quadrants make up this visualization, with quadrant 1 designating centrality and high density. Also taken into account are the articles' key themes. Low density and high centrality are fundamental and interdisciplinary themes correlated with the second quadrant. Quadrant 3 deals with niche or specialized topics and refers to low-centrality and high-density issues. The last quadrant refers to topics still in the nascent developing stage. The last two visualizations are clustering dendrograms and conceptual maps, respectively. Each of the subjects identified by BERT is represented by a conceptual structure map created by the conceptual structure visualization. Specifically, phrases taken from the papers' abstracts are subjected to Multi-Dimensional Scaling (MDS). Dendrograms (of various types) illustrate the conceptual structure and hierarchical analysis of the relationships between concepts.

3.2. Extraction and selection of bibliometric data

This study aims to gather and synthesize information from the existing literature on the main MMCs techniques used in building construction. The study adopts a mixed-method approach that incorporates both Natural Language Processing (NLP) and Systematic Literature Review (SLR) to provide a comprehensive analysis of the topic. The NLP component offers a detailed description, definition, and classification of MMC, enabling more effective detection of trends and gaps in the research. The SLR component provides a structured and explicit method that ensures the review is reproducible and verifiable [72]. The literature search was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, which is widely used in the medical field and provides a transparent and high-quality review [73]. PRISMA is widely used in medical disciplines because it generates an evidence-based result while improving the overall quality of the reviewed report by filtering the literature transparently [74]. The PRISMA protocol adopted in this study is depicted in Fig. 3 and details the sequential search and filtering steps, including the results obtained at each stage.

The data collection was conducted through SCOPUS, a globally recognized bibliographic database recommended by several experts [75,76] to guarantee the quality of the selected data. SCOPUS offers extensive coverage with access to articles and citations in the



RQ1: What MMC-based systems have been used in building construction in recent times?
RQ2: On what specific construction-related problems have these MMCs been applied?
RQ3: What are the gaps and the future research trends in the existing MMC literature?

Criteria 1:
Remove all journals with 1 article and with two or three papers, unless they belong to D1 and Q1, respectively, within the subject area of Building and Construction / Civil and Structural Engineering:

- J. Constr. Steel Res.
- Eng. Struct.
- Comput.-Aided Civ. Infrastruct. Eng.
- Thin-Walled Struct.
- Mathematics
- J. Environ. Manage.
- IEEE Trans. Autom. Sci. Eng.
- Environ. Impact Assess. Rev.
- Adv. Eng. Inf.

Criteria 2:
Eliminate coded affiliations with a single publication whose institution is not identifiable.

Criteria 3:
New elimination filter by specific keywords (using truncations):

Air Duct
*Airport**
Alternative
Agriculture
Alternative Energy
Antennas
Audio Acoustics
Biomass
*Bridge**
*Building Energy**
Building-Integration
PhotoVoltaic (BIPV)
Building-Integration
Wind Energy (BIWE)
*Climate**
Clinical Evaluation
Closed Circuit
Television
*Component-vehicle**
*Electric**
Electronic Data
Interchange
*Energy**
Hydration
*Gas**
Health Impact
Health Risks
Heating
Landscape Re-generation
Manufacturing
Facility
Petroleum Reservoir
Evaluation
Planets
*Planning**
*River**
*Road**
*Thermal**
*Urban**
*Urbaniz**
Vehicle Performance
Water Absorption

Refined Set (EXCL):
Remove papers that are outside the scope of the research after reading the title > abstract > full article.

Expansion Set (INCL):
Incorporate articles of interest after review of references and citations from the refined set.

Fig. 3. Steps of literature searching with filtering and results.

scientific and technical domain, enabling researchers to conduct backward and forward searches. The keywords were generated through a series of iterations that involved filtering and refining N-grams using TreeMap visualizations of frequently used terms and proper terminology. The keywords were searched for each of the five hierarchical categories that form the basis of the search strategy: (a) Subject area, (b) Scope, (c) Topic, (d) Subject matter, (e) Object of study. By combining 56 keyword strings using the Boolean operators "AND" and "OR" across the five categories, 2170 initial documents were found (as shown in step 1.1 in Fig. 3). These articles include 1013 (47%) conference proceedings, 860 (40%) journal articles, 132 (6%) conference reviews, 75 (3%) reviews, 61 (<3%) book chapters, 17 (<1%) books, and 12 (<1%) others. The initial query string was entered into the search algorithm on December 11, 2022.

The baseline sample undergoes a first screening process using four inclusion criteria (as outlined in step 1.2 in Fig. 3). This review covers a 47-year timespan from 1975 to 2022, as no relevant contributions were found in the database prior to that date. Only articles written in English, which are deemed universally accessible, were considered as potential literature. The selection was limited to original peer-reviewed scientific articles, including articles and state-of-the-art reviews. Only articles in their final publication stage were considered, and articles in press were excluded to ensure consistency in the content.

4. Quantitative analysis

4.1. General overview of the retrieved data

After the literature search and application of the inclusion and exclusion filters (as outlined in steps 1.1 to 1.3 in Figs. 3), 633 articles were selected from Scopus for stage 1. The NLP methodology supports quantitative analysis of the bibliometric features of the relevant literature. The sample comprises 582 journal articles (92%) and 51 review articles (8%). The study of MMCs is not recent; the term emerged around 2003 in the UK, but the idea of industrialized construction dates back to the 1960s. Despite fluctuations in its relevance, there was hardly any scientific production on the topic until the turn of the millennium (Fig. 4). However, there was a spike in interest in unconventional building systems between 2005 and 2009, which coincided with most of the classification proposals [39, 42–56] listed in Table 2.

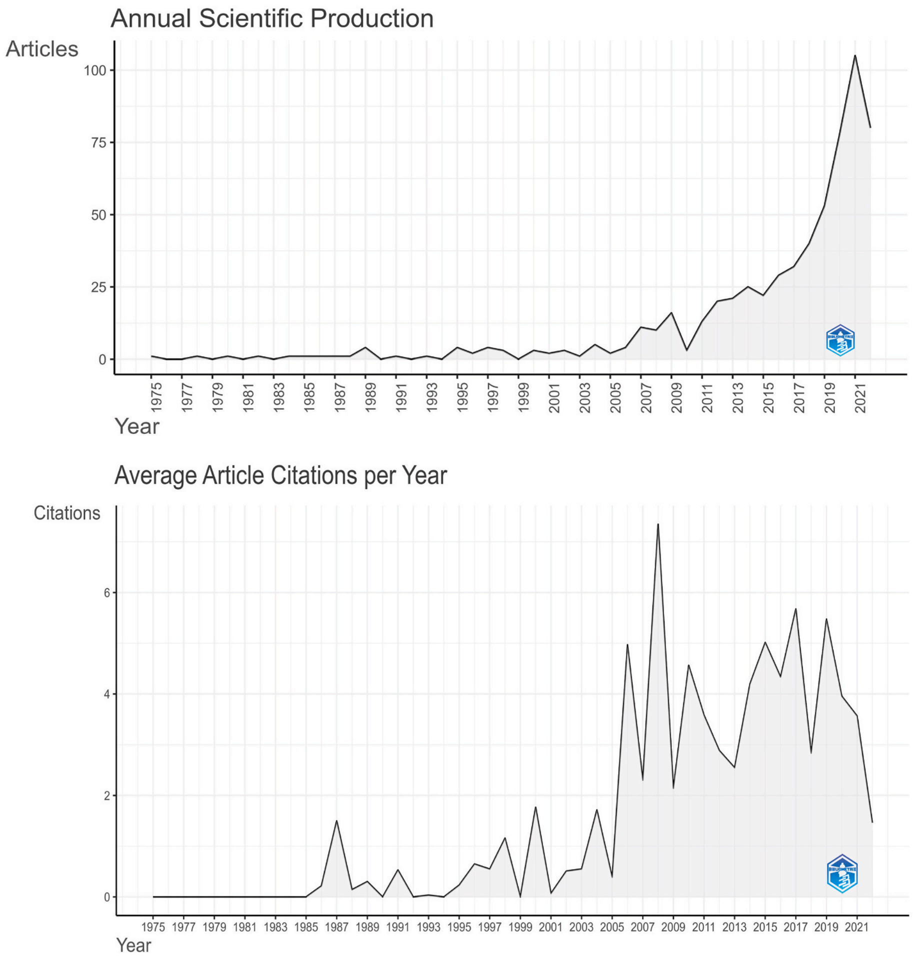


Fig. 4. Distribution in number of publications/citations (1975–2022).

The research on MMCs saw a significant spike in citation numbers from 2005 to 2009, when there was a surge of interest in unconventional building systems. However, the 2008 financial crisis led to a slowdown in the construction sector and a dip in scientific production until 2011. This date coincides with the context of the Industry 4.0, coined during the 2016 World Economic Forum (WEF) in Davos (Switzerland). From 2020 to August 2022, the research in this field has been overgrown, with 265 papers, more than 44% of all contributions being published in just this time frame.

4.2. Scientometric analysis

4.2.1. Distribution by journals

After the NLP process of semi-automatic selection (Figs. 3), 246 journals are distributed among the 633 articles analyzed. Fig. 5 shows the 17 most relevant sources containing more than five articles. The top eight journals alone account for one-third of the total number of publications, six of which have a very high impact. In particular, the ranking is headed by “Automation in Construction”, with 48 articles (8%) and 845 citations, which indicates a clear commitment to dissemination in MMC research. It is followed by "Sustainability" (7%), "Journal of Construction Engineering and Management" (5.3%), "Journal of Cleaner Production" (4.3%) and, further away, "Buildings" and "Journal of Building Engineering" (2.17% each). On the other hand, from a chronological point of view, since 1996, "Automation in Construction" has always been at the forefront regarding topics and trends in MMC. It was slightly surpassed in the number of articles published between 2011 and 2014 by "Journal of Construction and Management", resuming its trend exponentially until today.

4.2.2. Influential co-authors and top cited papers

With a sample of 633 papers, a long list of scholars spread across many countries was expected (Fig. 6). The threshold was set at a minimum of four papers to extract the most relevant researchers, resulting in 40 co-authors meeting the requirement. Fig. 6 shows a diagram structured according to the chronological production of each author between 2004 (when MMCs started to emerge) and 2022. The beige line depicts the author’s chronology, with Pan (2007–2020) and Al-Hussein (2008–2021) being the longest. Bubble size is provided based on the number of articles, with Al-Hussein publishing a maximum of 5 articles as a co-author in 2019 with a total of 266 citations. Finally, the intensity in the blue shade is proportional to the number of citations per year, with Al-Hussein [6] and Zhang [77] gathering 66.5 and 68 citations per year, in 2019 and 2021, respectively. At the opposite extreme, there are emerging authors with a short time trajectory but high productivity in publications, with three articles only in the first half of 2022 [78]. As Fig. 4 already warned, it can be seen that the highest peak of contributions occurs in 2021 (taking into account 2022 as a year still in progress), in which 26 of the 30 authors contribute one or more articles. The data produced by this analysis can help in subsequent studies to identify the leading authors in MMC according to their experience and production over time, whether it is a consolidated authority or emerging groups. This approach will make it easier for researchers to keep abreast of updates in the field and even develop plans for future collaboration between different institutions.

Table 4 includes the top 20 papers (2007–2022) with more than 55 citations out of 98 articles with at least one citation. Duplications by research groups have been eliminated, considering only one contribution linked to the main author. This excerpt of articles shows that in the last 15 years, they mark different trends in studies on MMC research. The two most cited articles [7,79], by the same

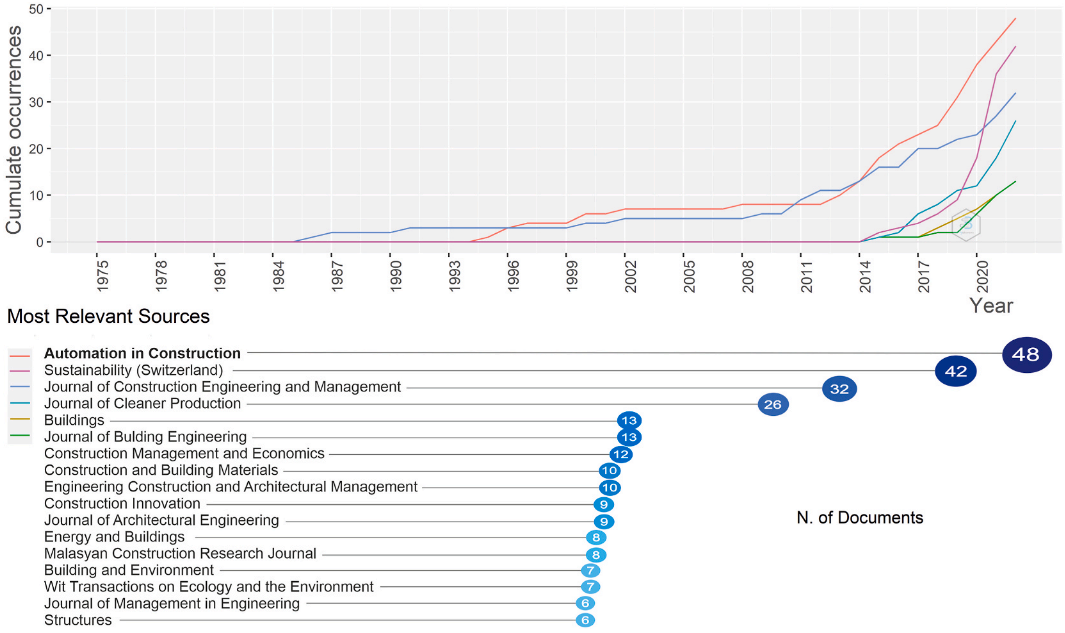


Fig. 5. Evolution of the growth of the most relevant sources.

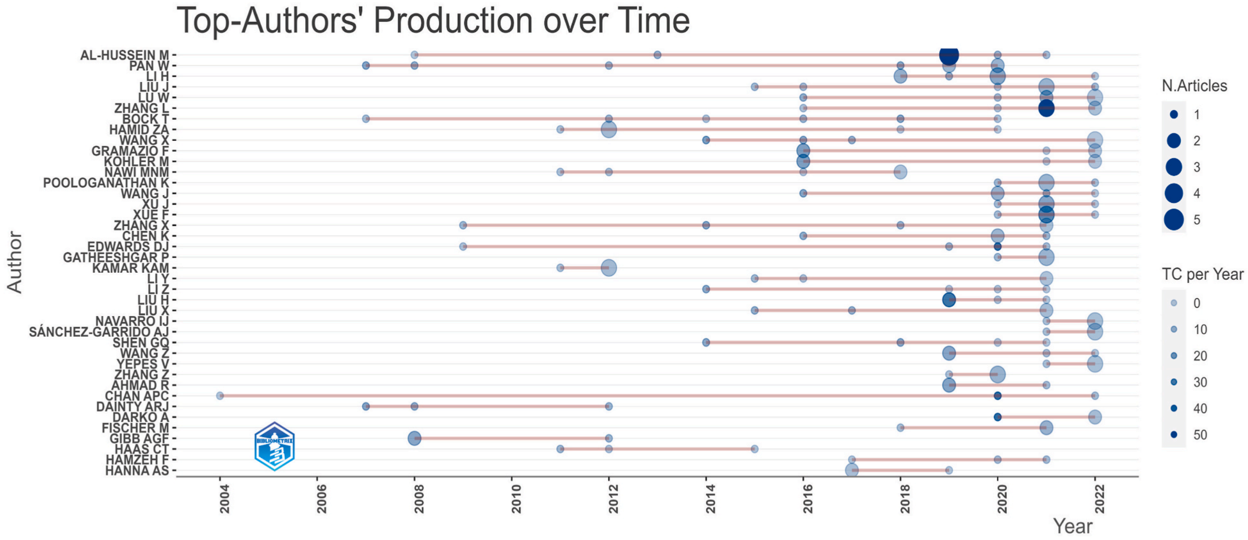


Fig. 6. Top−authors' production over the time.

Table 4
Top cited articles in MMC.

Main author	Year	Title	Source	TC	TCbY	Ref
Pan, W.	2007	Perspective of UK housebuilders on the use of offsite modern methods of construction	Construct. Manage. Econ.	229	14.3	[7]
Pan, W.	2008	Leading UK housebuilders' utilization of offsite construction methods	Build. Res. Inf.	159	10.6	[79]
Darko, A.	2020	Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities	Autom. Constr.	138	46.0	[80]
Yin, X.	2019	Building information modelling for off-site construction: Review and future directions	Autom. Constr.	128	32.0	[6]
Zhang, X.	2014	Exploring the challenges to industrialized residential building in China	Habitat international	127	14.1	[81]
Pan, Y.	2021	Roles of artificial intelligence in construction engineering and management: A critical review and future trends	Autom. Constr.	126	63.0	[77]
Li, Z.	2014	Measuring the impact of prefabrication on construction waste reduction: An empirical study in China	Resour. Conserv. Recycl.	118	13.1	[82]
Mao, C.	2016	Cost analysis for sustainable off-site construction based on a multiple-case study in China	Habitat international	101	14.4	[83]
Ibrahim, Y.M.	2009	Towards automated progress assessment of workpackage components in construction projects using computer vision	Adv. Eng. Inf.	92	6.57	[84]
Willmann, J.	2016	Robotic timber construction — Expanding additive fabrication to new dimensions	Autom. Constr.	91	13.0	[85]
Yu, H.	2013	Lean Transformation in a Modular Building Company: A Case for Implementation	J. Manage. Eng.	89	8.9	[86]
Pan, W.	2012	Establishing and Weighting Decision Criteria for Building System Selection in Housing Construction	J. Constr. Eng. Manage.	87	7.90	[87]
Liu, X.	2015	Behavior of High-Strength Friction-Grip Bolted Shear Connectors in Sustainable Composite Beams	J. Struct. Eng.	83	10.3	[88]
Niu, Y.	2016	Smart Construction Objects	J. Comput. Civ. Eng.	79	11.2	[89]
Pan, M.	2018	A framework of indicators for assessing construction automation and robotics in the sustainability context	J. Cleaner Prod.	73	14.6	[90]
Li, X.	2018	RBL-PHP: Simulation of Lean Construction and Information Technologies for Prefabrication Housing Production	J. Manage. Eng.	71	14.2	[91]
Linner, T.	2012	Evolution of large-scale industrialization and service innovation in Japanese prefabrication industry	Construction Innovation	70	6.3	[92]
Teng, Y.	2017	Analysis of stakeholder relationships in the industry chain of industrialized building in China	J. Cleaner Prod.	59	9.8	[93]
Liu, X.	2017	Flexural performance of innovative sustainable composite steel-concrete beams	Eng. Struct.	58	9.6	[94]
Martinez, P.	2019	A scientometric analysis and critical review of computer vision applications for construction	Autom. Constr.	55	13.75	[95]

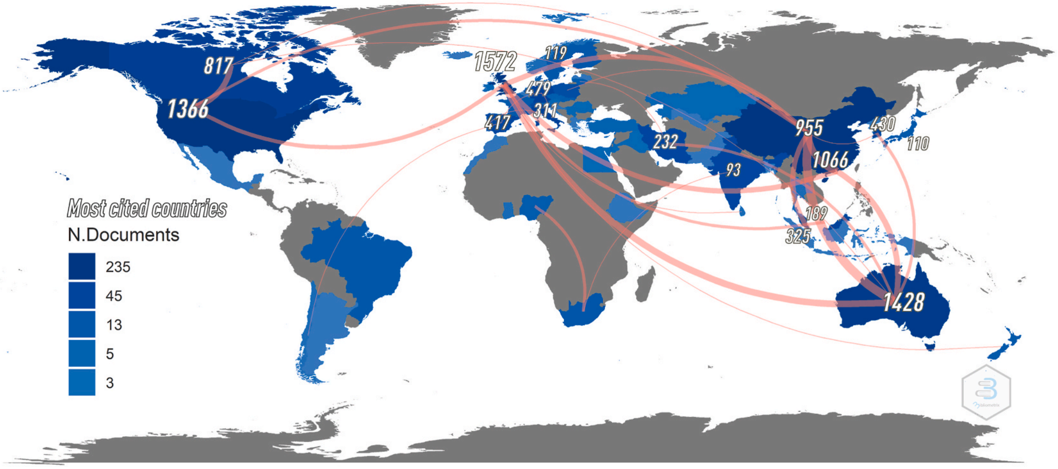


Fig. 7. Map of scientific production with the most cited countries and social structure of collaboration.

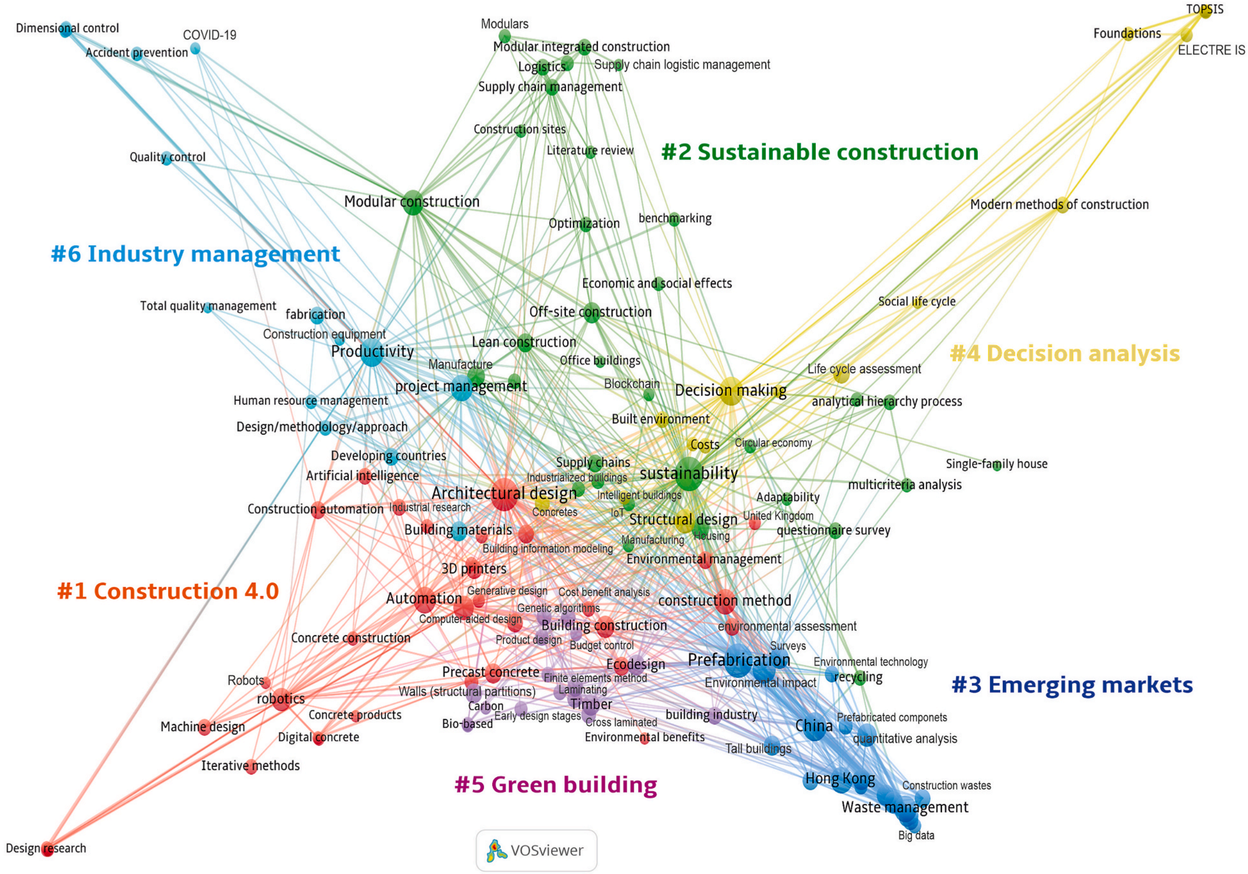


Fig. 8. Scientific analysis map with co-occurrence clusters of keywords based on MMC.

author, are also the oldest and explore, through questionnaires to UK housebuilders, the factors influencing the implementation of off-site MMCs. Among the most referenced articles, they are followed by three state-of-the-art reviews from the last three years, two of which focus on AI applied in the AEC industry [77,80] and the other on the BIM approach to OSC [6]. Finally, three articles dedicated to case studies in China also have above 100 citations. Specifically, they explore the opportunities offered by industrialized buildings [81], study waste reduction through prefabrication [82], and analyze the costs for sustainable OSC [83]. Recent articles are an example of the impact of the Asian market on MMC research, especially in prefabrication. Fig. 8 highlights China and Hong Kong stand out with their clustering. The comparison of citations between articles over a timespan, such as that adopted in this study, does not necessarily have to correspond to a greater or lesser impact based on the number of total citations (TC). For this reason, the normalization of total citations by year (TCbY) is used to identify the most influential articles. As shown in Table 4, the article with the most accumulated citations (TC = 229) does not coincide with the one with the most significant influence on the scientific community (TCbY = 63).

4.2.3. *Active countries and geographic collaboration*

Fig. 7 represents the global geographic distribution of MMC research on a world map to facilitate the reader's recognition of the location of critical contributions and publication interactions. The strength of the blue color shows proportionally the number of publications accumulated between countries; the darker, the greater the intensity. The number of citations from the most active countries is added in white. The coral-colored links show the interaction between each country's research, and a greater thickness of the link indicates that the connection relationship is strong. The highest number of papers (56), with 1572 citations, has been published in the UK [7,79,84], which is consistent with the fact that this is where the term MMC emerged. At the forefront of prefabrication and OSC, China [81–83] reached the same number of papers but reduced citations to 955. However, as detailed in Section 2.1.1, the genesis of industrialized construction cannot be dissociated from other countries such as the United States (PPMOF) or Australia (OSM). The latter, with an average number of article citations of 47.60, outperforms the UK and the USA [87,89], with averages of 28.07 and 24.84. This means that with fewer publications, the 30 articles from Australia [14,80] achieve much more influence than in the rest of the countries. Canada [6] and Hong Kong [93], with 32 and 22 articles, complete the top 6 countries with the most prominent scientific publications in MMC. However, the Asian region stands out with 1066 citations compared to 817 for Canada, which limits its relations almost exclusively to the USA.

4.3. *Thematic classification*

To address the qualitative analysis in the following section, it is necessary first to obtain the thematic categories with the current trends in MMC research. For this purpose, a co-occurrence analysis is performed, studying the number of times that two terms (or string of characters) coincide at least in more than one document. This systematic and objective process uses scientometrics, co-words, and network analysis to extract relationships between topics from article content [96].

The bibliometric mapping software VOSviewer version1.6.18 [97] was used for this analysis to generate knowledge maps with different appearances, such as clusters with sizes according to frequencies or co-occurrences. In addition, it implements a probabilistic analysis with the mathematical algorithm named Kernel. This function not only performs a count but also allows the size of the meaning of a term that is represented next to another since they are likely to be associated by the iterative process it applies. For the bibliometric treatment of the data, the Bibexcel tool was used, which consists of sophisticated free software [98] that performs mathematical calculations on bibliographic references or texts. It obtains frequencies and relationships between terms, generating matrix graphs that are subsequently drawn and visualized in VOSviewer. The scientific keyword map was created by extracting the "KW" field (author keywords) and performing a "co-occurrence" analysis with the selection "make pairs via list box".

Fig. 8 shows the resulting map to visualize the co-occurrences between the authors' keywords after eliminating the duplicated general and items that generate the most noise, such as "Construction industry", "Construction", "Sustainable development" or "Life cycle". The circles represent a term whose size is proportional to the number of published articles. The closeness or remoteness of one node to another reflects the proximity relationship of each pair of terms in a text unit. The colors indicate clusters of words that are relatively related to each other. As Fig. 8 shows, six major clusterings stand out for the MMCs used in the construction, each of the categorized topics with a relevant dominance over other subcategories of concepts to which it is connected.

1. Cluster one "Red": Construction 4.0 (Architectural design, Automation, Construction method, Robotics, 3D printers, Computer aided design, Precast concrete, Building information modeling, Artificial intelligence, Cost benefit analysis, United Kingdom); References [6,26–29,77,80,84,85,89,90,95,99–125].
2. Cluster two "Green": Sustainable construction (Sustainability, Modular construction, Lean construction, Off-site construction, Supply chain management, Analytical hierarchy process, Construction sites, Economic and social effects, Optimization, Adaptability, Circular economy); References [88,94,126–141].
3. Cluster three "Dark blue": Emerging markets (Prefabrication, Environmental impact, China, Hong Kong, Waste minimization, Quantitative analysis, Surveys, Big data, Tall buildings, Conservation); References [8,14,16,21,25,45,47,81,82,92,142–155].
4. Cluster four "Yellow": Decision analysis (Decision making, Structural design, Life cycle assessment, Social life cycle, Cost, Modern Methods of Construction, TOPSIS, COPRAS, ELECTRE IS); References [17,22,78,83,156–167].
5. Cluster five "Purple": Green building (Ecodesign, Timber, Cross laminated, Wall (structural partitions), Early design stages, Product design, Mathematical programming, Genetic algorithms, Carbon); References [168–182].
6. Cluster six "Light blue": Industry management (Productivity, Project management, Building materials, Quality control, Construction equipment, Accident prevention, Developing countries); References [4,7,9,15,20,24,29,31,33,37,42,46,52,54,79,86,91,93,183–197].

5. Qualitative analysis

This section analyzes the research subcategories deployed from each thematic category obtained in Fig. 8, identifying up to 18 hot topics under the six main themes. However, only 180 articles were used to move on to the qualitative analysis of the 633 quantitatively analyzed, limited to 20 years between 2002 and 2022. These articles were selected by careful manual SLR (steps 2.1 to 2.3 in Fig. 3) until a synthesized but representative set was obtained to serve as a global sample to discuss MMCs.

5.1. Construction 4.0 (number of articles = 51)

Industrialization implies a high degree of organization, requiring different tools and technology integrated into the work processes [28]. It must allow the exit to a very competitive market in a society that increasingly demands economic, fast, quality, and profitable construction. To achieve this, the current industrial 4.0 model [26] is based on a) the automation and optimization of processes, seeking efficiency in deadlines; b) the implementation of new digital technologies, constructively defining the building almost in its entirety in the initial design phase, avoiding problems and unforeseen events in the execution phase; c) skilled labor, since applying these tools requires professional specialization.

5.1.1. Computer-aided design, building information modeling and rendering

Computer-aided design (CAD) and related technology are not recent [99]. In the case of industrialization associated with MMCs, the integration of Building Information Modeling (BIM) is one of the leading and most widely used tools [6,100]. It facilitates the exchange and management of building data in real-time and throughout the building's life cycle [101,102]. BIM-based approaches using 3D architectural modeling and geometry-based design automation have been realized, capable of creating up to 1500 new precast and cast-in-place concrete design options in as little as 30 min [103]. Researchers have developed prototypes that integrate 4D BIM applications to plan the layout of concrete joints in real-time [104]. Other scholars have focused on CAD automation and computer-aided manufacturing (CAM), from bricks [99] to timber-framed panels to generate BIM and fabricate the automated construction of residential modular buildings [105]. BIM integration has also been used with other analytical algorithms to parameterize the design of precast drywall by optimizing them from an ecological, economic, and aesthetic point of view [106]. These design and digital data management tools are decisive when comparing conventional construction methods with MMCs. They facilitate decision-making based on sustainability criteria [19,107], being especially useful to implement during the earliest phases of design [108] to ensure quality and complete control of the building prior to on-site construction. Regarding dismantling or rehabilitating the building, BIM efficiently provides all the information related to materials and their recycling [101], enhancing the circular economy.

5.1.2. Blockchain, digital twin, computer vision and internet of things

Blockchain technology enhances the precision of MMC on-site assembly [109]. It ensures a secure and controlled digital environment for the BIM model where the project is developed, enabling traceability of the building's life cycle processes [110]. This is particularly beneficial in decentralized project settings. This multidisciplinary approach aims to align the building's actual performance with the design and expectations of the developer. The digital twin [111] combines the information required for commissioning and monitoring the finished building. The digital twin, updated in real-time through monitoring, provides data on the building's state and predicts its behavior in uncertain circumstances. Advancements in technology, such as IoT [112] and computer vision [84,95], further enhance the digital twin and improve decision-making for MMC innovation, making it directly applicable to the management and maintenance of buildings and critical infrastructure.

5.1.3. Artificial intelligence, machine learning and deep learning

Building managers in MMC-based constructions must have the ability to understand and accurately assess the results of monitored models. These models have real-time updated data in their digital twin. However, it can be challenging to understand the data and the root causes of changes in building behavior, mainly related to structural behavior throughout its lifespan. Artificial intelligence (AI) [77,113] and machine learning (ML) [80] have long been used in the civil engineering and construction industry to analyze large amounts of data and identify patterns and correlations. Recently, there has been a significant advance in deep learning (DL), a more advanced form of ML that uses neural network-based algorithms. Studies have shown that integrated modular construction can benefit from combining virtual prototyping and transfer learning techniques to develop a module detection model based on mask regions through a convolutional neural network [114].

5.1.4. Automation, robotics, 3D printing and additive manufacturing

In addition to the already developed concepts of digital design, information and communication technologies, or AI, topics such as automation [115,116] and robotization [107,117] are necessarily associated with the innovation of the so-called "smart construction" on which MMCs are based. With the help of cognitive learning, these automated systems can accomplish or increase tasks to enhance performance and resolve better solutions to decisions that traditionally require human judgment. Although the integration of automation in architecture has seen a slow progression, an increasing number of construction companies are implementing automated systems and procedures into their operations [118]. The development and implementation of automation and robotics in the construction industry present new opportunities to address various building needs within the sustainability framework [90]. Researchers have introduced innovative robotic automation systems with various applications, including the digital fabrication of unique timber structures [85,119], assembling steel beams [120], constructing commercial cavity blocks [121], and using mobile masonry robots on construction sites [122]. The growth of MMC-based industrialized building prefabrication has been spurred by advances in 3D printing (3DP) technology. As construction projects become increasingly complex and cost-conscious, this technology has been proven to be a game-changer. 3DP has created models of retaining and shear walls with non-standard shapes for a single floor of a reinforced concrete building, including reinforcement [123]. Other research has explored the potential of fused deposition modeling (FDM) for 3DP fabrication of a lightweight cellular lattice structure reinforced with long fibers in complex and unconventional structures [124].

Although among the most promising Construction 4.0 technologies, BIM, AI, 3DP, or ML are at the forefront, there are still many gaps to be filled by combining all their capabilities in terms of material and design flexibility, cost efficiency, operational agility, and sustainable practices [125]. For example, 3D-printed houses could be explored as a temporary shelter solution after disasters such as the recent ones: forest fires in North America, floods in Pakistan, the conflict in Ukraine, and earthquakes in Indonesia or Turkey.

Before a catastrophe, some elements, such as walls, can be prefabricated and stored for later assembly. In addition, houses can be 3D printed on the ground using machines, while aerial robotic drones scan the area and create 3D landscape models with BIM systems. Some drone prototypes can already fix pipes. In the future, they could be equipped with AI and ML to assist in various aspects of the construction process, potentially reducing the need for human labor and enabling the rapid establishment of temporary shelters or housing solutions.

5.2. *Sustainable construction (number of articles = 23)*

Sustainability has evolved from a visionary idea to an imperative. The European directives and the 17 Sustainable Development Goals (SDGs) for 2030 provide a roadmap for aligning all economic activities with a balance of economic viability, environmental protection, and social welfare. MMCs strongly align with the three dimensions of sustainability.

5.2.1. *Sustainable design*

The construction industry is a significant contributor to environmental stress, making it crucial to pursue sustainability. However, until recently, little attention has been given to finding environmentally friendly solutions in the design phase of the building life cycle [126]. As a result, optimizing structural designs using mathematical procedures based on iterative methods to achieve functionality with minimal use of materials [127] has become an area of growing interest [128] to reduce the environmental impact of material extraction and processing. Research is being conducted to minimize material consumption and embodied energy [129] and reduce carbon dioxide emissions [130]. In addition, recent studies have taken a comprehensive approach to sustainability assessments, incorporating life cycle assessment methods such as ReCiPe, economic, and social factors [131]. There is also ongoing research on using innovative materials to enhance the sustainability of buildings [94,132]. Another promising trend in reducing environmental impact and enhancing socio-economic aspects of construction is the use of pre-manufactured modular sections [133].

5.2.2. *Sustainable production*

The production life cycle of buildings has become a critical factor in assessing their environmental impact. As a result, research has been conducted to identify ways to enhance the sustainability of building processes [134]. The environmental and sustainable benefits of MMCs have been emphasized by multiple studies [135,136], indicating a need for a change from traditional on-site construction practices [137]. examines the potential benefits of using wood-based construction techniques based on public perception towards wood buildings and also reveals positive feedback for OSC.

5.2.3. *Sustainable operations*

Modular OSC is a cutting-edge building method involving prefabricating components assembled on-site. This method results in high-quality, environmentally friendly buildings that are built faster and generate less waste. The challenge of managing the supply chain is one of the main limitations of modular OSC. However, recent research has shown that optimizing supply chain management can lead to greater sustainability [138]. Efforts are being made to reduce carbon emissions in the supply chain [139,140] and to explore the potential socio-economic benefits of fast construction methods in prefabricated buildings [141].

5.3. *Emerging markets (number of articles = 27)*

Sustainable architecture has gained global prominence, particularly in developing nations. In Asia, particularly China, where there has been significant economic and population growth, the implementation of sustainability in the construction industry is of particular interest. In the past, however, China was one of the largest producers of pollution and waste, lacking consideration for sustainability in its construction industry.

5.3.1. *Asia*

In recent years, China has shifted from being a world factory to having a leading industry of its own. Studies have been conducted to understand the factors contributing to the growth of the prefabrication industry in Asia, with some focusing on future trends in countries such as Japan [92]. The public's perception of emerging markets in Asia has also been explored [142,143], revealing positive feedback for off-site production practices [144]. Despite this, there are still barriers hindering the implementation of MMC and industrialized building systems in Asia, particularly the cost [8]. Researchers have analyzed the cost composition of prefabrication processes [145] and products to demonstrate the economic benefits of traditional construction methods [16]. Other studies have explored the impact of lean practices on project value [146] and the role of corporate responsibility and experience on the quality of prefabrication production in China [147]. Additionally, the structural response of modular construction systems in high-rise buildings and the development of timber-based construction practices in China have been studied [148,149]. Further encouragement and development through strategies and policies are needed to support the growth of the industrialized building industry in Asia [21,47,81].

5.3.2. *Prefabrication*

The terms "industrialization," "prefabrication," and "modular construction" can be easily confused. A fully industrialized building is considered "prefabricated" if its components are not assembled on-site. These homes are delivered to the construction site already finished and only require connection to utilities. On the other hand, modular construction involves putting together several prefabricated modules to create a building. In the Asian market, the development of high-rise modular prefabrication has gained momentum as a way to grow cities sustainably. Research has explored various global prefabrication methods, specifically in the Australian market [150]. Optimizing prefabrication processes is also a focus of current research [151]. The benefits, performance advantages, and limitations of prefabricated elements in construction have been analyzed and summarized in Ref. [14]. Despite its sustainability benefits, research is still being conducted to understand why the precast construction industry remains an emerging market and has yet to become widely adopted [152,153].

5.3.3. Waste reduction

Most MMCs make it easy to assemble and disassemble buildings, thereby significantly simplifying the recycling of components and materials. These recyclable materials can then be reintegrated into the industrial supply chain, helping to minimize the environmental impact. Recent studies have explored how prefabrication technology can effectively curb construction waste [82]. One study of 114 actual high-rise building projects found that prefabrication can average a reduction of 15% in construction waste compared to traditional construction methods [154]. Due to the increasing focus on minimizing waste from prefabricated components, researchers have investigated the potential use of BIM technology to achieve this goal [155].

5.4. Decision analysis (number of articles = 17)

The subject of decision-making in building construction continues to captivate researchers. The attributes that define a building are frequently interrelated, causing the advantages or disadvantages of various building alternatives to vary depending on the criteria evaluated. To comprehensively compare different MMCs and conventional methods, decision analysis strategies are employed to optimize the results and aid decision-makers in the selection process.

5.4.1. Life cycle assessment (LCA)

The construction sector accounts for nearly 40% of the carbon emissions into the atmosphere and thus plays a crucial role in mitigating the effects of climate change. However, only what can be quantified can be addressed. LCA is a methodology that objectively assesses environmental impacts and aids decision-making. The current state of LCA applied to MMCs has mainly focused on environmental performance [17,22]. As outlined in the ISO 14040 series of standards, this methodology can also evaluate socio-economic impacts as they share some common elements that provide valuable comparative data for decision-making in new projects or improvement initiatives. Environmental [156] and economic [83] impact assessments of MMCs have been conducted for over a decade, as they are mature methodologies established in 2006 and 2008. Some scholars have investigated environmental assessment by developing BIM-based LCA methods for prefabricated buildings that can support automated assessments throughout the life cycle [157]. After the creation of the SDGs in 2015, more attention has been given to three-dimensional approaches to sustainability, including social aspects, which are more challenging to evaluate than economic or environmental factors. Recently, some comprehensive research on building sustainability has emerged. In Ref. [158], a Life Cycle Sustainability Assessment (LCSA) is conducted on different MMC-based foundation and soil improvement alternatives, combining the social assessment with impacts of the transient state (short-term) and the steady state (long-term). Therefore, more research is needed to integrate the social dimension into the SDGs.

5.4.2. Multi-criteria decision making (MCDM)

This issue is of great significance in construction engineering, especially in sustainable design, where complex challenges involving multiple and often conflicting factors must be addressed. Traditional Multi-Criteria Decision Making (MCDM) techniques, such as AHP and VIKOR, have been employed to subjectively weigh and choose between precast concrete, steel, and laminated timber deck structures [159]; and SWARA and COPRAS have been used to prioritize green building materials [160]. The efficiency of precast and in-situ construction systems was evaluated through a hybrid MCDM approach [161]. The Delphi method was utilized to formulate relevant criteria, DEMATEL to analyze their impact, ANP to assign weights, and TOPSIS to determine rankings. In the context of a tall building in Australia [162], studied the selection of the most sustainable construction method among three industrialized and one robotic alternatives using AHP as the most commonly used MCDM technique. In these cases, social impacts are often limited to simple factors such as aesthetics or construction time, without considering other social aspects related to building construction, maintenance, and demolition that align more closely with the SDGs [78]. consider social criteria such as job creation, fair wages, public engagement, and the safety and health of users and workers. The economic, environmental, and social impact categories are combined into a comprehensive sustainability index through the combination of SAW, COPRAS, TOPSIS, VIKOR, and MIVES. Further research is necessary to understand stakeholders' priorities for MMCs adoption, especially in Europe, where their adoption rate remains low compared to conventional methods [163]. provides a thorough analysis of the barriers to modular construction in Germany from a developer's perspective using fuzzy DEMATEL.

5.4.3. Decision support systems (DSS)

DSS can streamline the resolution of complex problems and enhance objective and accurate decision-making. In Ref. [87], a multi-methodological approach was employed with over 50 criteria, categorized by quality, expenses, timeline, sustainability, safety, health, contracting, process, and regulatory compliance. The study in Ref. [164] in Malaysia identified material consumption, waste generation, and disposal as crucial factors of MMCs. It proposed a systematic strategy to improve environmental performance by conducting a SWOT analysis to inform upstream decision-making [165]. created a classification matrix to aid decision-making when designing or revamping OSP systems in residential architecture. In other cases, hybrid techniques have been used in uncertain scenarios, including a neutrosophic set approach with N-AHP [166] to address the uncertainty in expert group evaluations. In Ref. [167], an ANP-ELECTRE IS model was calibrated for sustainability assessment criteria in building structures, which resulted in greater consistency by automating the clustering of input data and reducing expert judgments by over 90%.

5.5. Green building (number of articles = 17)

The terms "green" and "sustainable" are often used interchangeably, but sustainability involves a balance of the three pillars: economy, environment, and society. A green building prioritizes environmental health by efficiently and minimally impacting land, water, energy, and resources during construction and service life. It incorporates various practices and techniques to reduce or eliminate the negative impact on the environment and human health.

5.5.1. Ecodesign

In the green building industry, there is significant interest in natural materials for structural applications, leading to the emergence of the Eco-design approach as a means to support sustainable building practices. A particular focus has been placed on using timber-based construction elements to reduce the emissions and waste generated by traditional construction materials. The Eco-design approach is closely linked to the use of timber in all its forms as a primary construction material. In particular, industrialized timber has proven to be a precious alternative for green building construction [168,169]. As a result, the use of Cross-Laminated Timber (CLT) elements has emerged as an environmentally friendly alternative to traditional prefabricated solutions [170,171]. Additionally, research has been conducted on the performance of alternative natural elements, such as unprocessed bamboo, as efficient building materials [172].

5.5.2. Eco-efficiency

The increasing interest in using natural materials in construction has prompted the scientific community to evaluate their structural performance. Significant efforts have been focused on analyzing CLT elements' stiffness and strength efficiency [173]. Research has covered the numerical and experimental assessment of the bending strength of CLT panels, their response to seismic conditions [174], and the structural analysis and design of efficient connections between CLT and steel elements [175]. In addition to CLT-based solutions, there is also growing attention on the structural analysis of bamboo-based solutions [176] and the development of simple processing technologies to make it a competitive alternative to conventional construction materials [177]. Moreover, research has been conducted on the structural efficiency of natural elements like oak logs, which due to their irregular shape, have been deemed uncompetitive in processing and often discarded as valuable construction materials [178].

5.5.3. Circularity

A significant trend in the construction industry is adopting circular economy strategies [179]. The construction sector's conventional "buy-use-dispose" approach has faced criticism for generating a large amount of waste at the end-of-life (EoL) of the built environment. In contrast, the circular economy aims to minimize waste at the EoL stage and create valuable waste that can be recycled or repurposed as building materials.

In line with the circular economy trend, various practices have been studied for their contribution to the circularity of the built environment, such as implementing lean construction principles during the building construction phase [180]. Research has also been conducted on utilizing digital technologies to achieve a circular economy across industries [181]. Another noteworthy trend involves adopting innovative materials and solutions that positively impact the circular economy, such as using bio-based walls instead of traditional prefabricated wall panels [182].

5.6. Industry management (number of articles = 45)

One of the significant challenges architects and construction professionals need to improve is the inefficiency of traditional construction techniques [29]. Delayed decision-making and missed deadlines result in low economic returns. Modular and Manufactured Construction aims to guarantee that every project is both high-quality and profitable [9]. To achieve this, streamlining the production process through technology and effective organizational management is critical in establishing an industrialized and efficient building production model.

5.6.1. Lean construction, productivity and quality/security control

Lean Construction (LC) is a critical component for implementing industrialized architecture based on MMCs [86,91]. This approach focuses on creating practical tools for the execution phase, particularly in coordinating and making decisions during the manufacturing process and assembly of elements. The objectives of LC include improving design and manufacturing efficiency, increasing standardization and customization, reducing labor requirements and costs, and minimizing waste in materials and construction [183,184]. Productivity [185] is ultimately the goal of all this incorporation of advanced processes and technologies in design, production, manufacturing, and management for MMC-based construction [186]. MMCs systematically manufacture components in a factory setting using machines, robots, and skilled workers. Most constructions, especially modular ones, are made under cover and optimal working conditions [20]. Modular construction, in particular, is carried out under optimal working conditions and can simplify mass customization [187] in engineer-to-order environments. Some methodologies, such as the graph-based approach, have been developed to optimize the design of modular buildings by applying a clustering algorithm and using iterative methods combined with BIM tools [188]. Building quality depends on on-site work in traditional construction, and productivity suffers greatly, especially in labor-intensive tasks such as formwork [189]. These on-site operations are only sometimes performed by qualified personnel and in variable environmental conditions in the open air, resulting in numerous occupational accidents. Some methodologies, such as the graph-based approach, have been developed to optimize modular building design [190]. In terms of labor productivity evidence, a contractor interaction study was conducted to investigate the impact of BIM on labor performance on commercial projects, which revealed an increase in labor productivity in modeled and prefabricated areas by as much as 240% [191]. In addition, it has been possible to develop innovative recruitment methods to improve recruitment strategies in the organization of specialized tasks [192]. In this context, analytical methodologies have also been developed to characterize the variability of productivity in budgeting labor costs [193] specific to industrialized construction.

5.6.2. Supply chain, manufacturing/assembly

The pursuit of efficiency in MMCs in an Industry 4.0 setting requires dividing the work into various tasks [4]. This division allows each professional to play a crucial role in the building's production, construction, and management chain [15,54]. This revolution has transformed construction supply chains hitherto oriented exclusively to transporting raw materials. The revolution in construction has changed the traditional supply chain, which used to focus solely on transporting raw materials. Mathematical models have been tested in MMC projects to optimize manufacturing, transportation, and inventory for school dormitories to design logistics configurations with reduced risk [194]. The Just-in-Time (JIT) approach has been studied for supply chain performance management to evaluate the environmental and economic impact of prefabricated products in sustainable development [195]. The social dimension of sustainability is also a concern, and reducing scheduling delays remains a challenge. Although some integrated performance-based duration estimation models have been developed [196], or scheduling calendars have been developed from genetic algorithms and multiple constraints [197], further sophistication is required to solve the problem entirely. In a conventional building, changes and weather conditions often result in construction delays. However, with MMCs, manufacturing is automated, and decisions are made in advance [24], reducing the need for improvisation and speeding up the construction process [46].

6. Discussion

6.1. Trend analysis

In this section, the analysis of trend topics will be introduced. The density and centrality of the graph will be used to carry out this analysis of trend topics. The graph is built from bigrams of the abstracts, performing a process of stopwords and lemmatization to ensure a better quality of the clusters. The Walktrap (WT) method [198] was used to construct the clusters. The WT algorithm uses a hierarchical agglomerative method to get the clusters. The result is shown in Fig. 9. The figure considers four quadrants: motor clusters in the first quadrant, niche themes in the second quadrant, emerging themes in the third quadrant, and primary groups in the fourth. In the first quadrant, the topic that stands out (in orange) corresponds to sustainable development focused on urban development and planning in conjunction with waste management. This orange group is related to the green cluster shown in the fourth quadrant; in this cluster, the development of new materials, structural design, and life cycle analysis with a focus on sustainability and green building

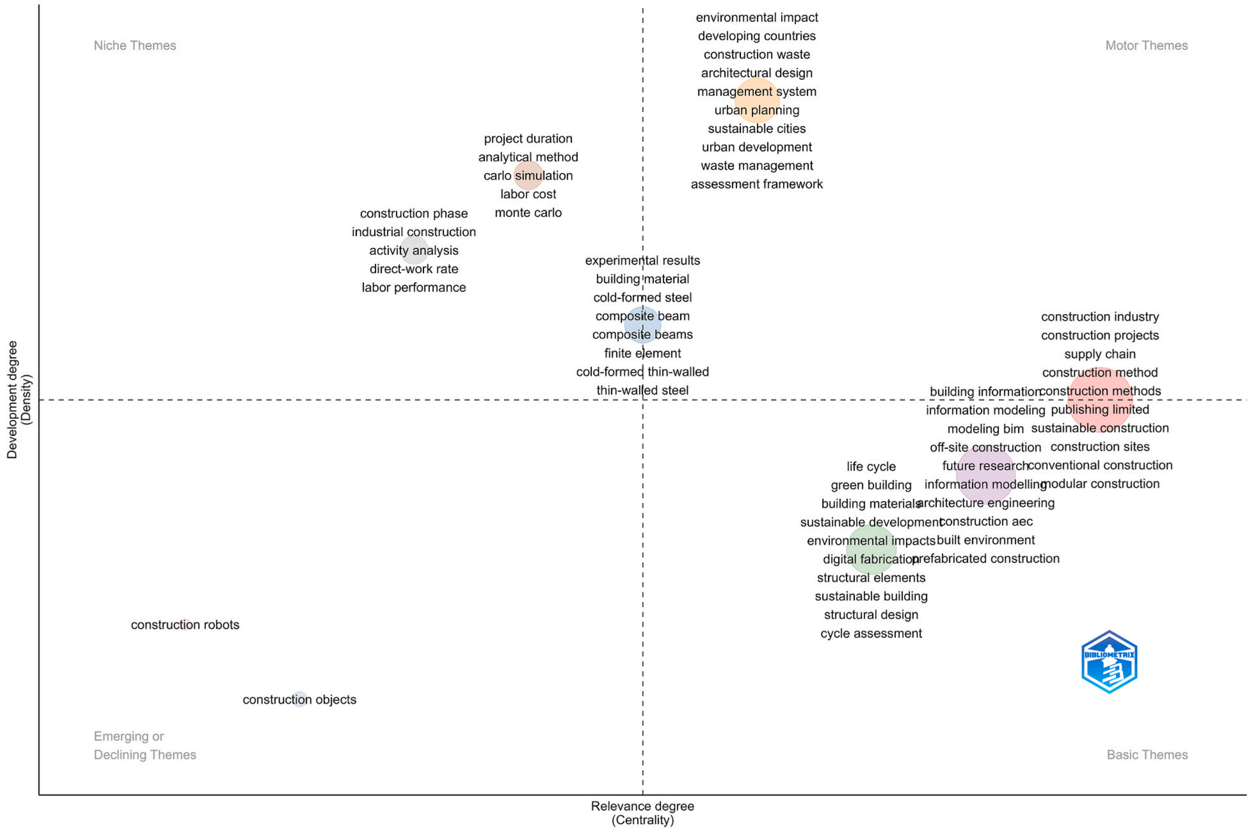


Fig. 9. Trends topic analysis based on abstract on MMC selected papers.

stand out. Therefore, sustainability is an essential and driving theme in MMC.

On the other hand, the purple cluster of the fourth quadrant highlights the administration of information for management focused on different construction methods such as AEC, precast, and BIM. This cluster is related to the cluster located between the first and fourth quadrants, which relates construction projects to the supply chain and different types of construction methods. Therefore,

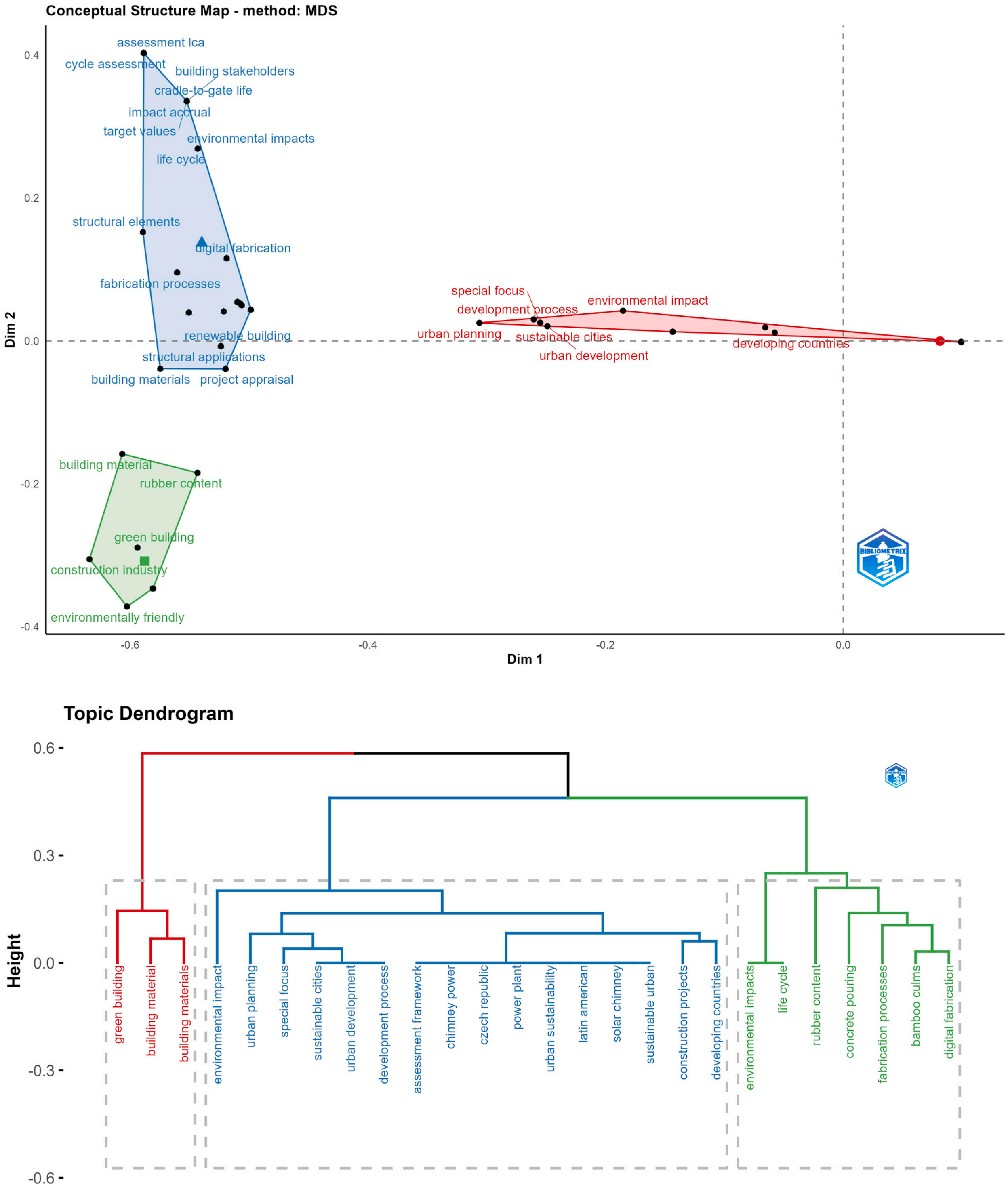


Fig. 10. Dendrogram and conceptual structure analysis for green building. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

another essential and driving theme corresponds to industry management. The industry management topic has a niche line in the second quadrant which exploits all the simulations and Monte Carlo methods to estimate the duration of projects and associated risks. Finally, in the third quadrant, we find themes related to industry 4.0 about robotization and process automation.

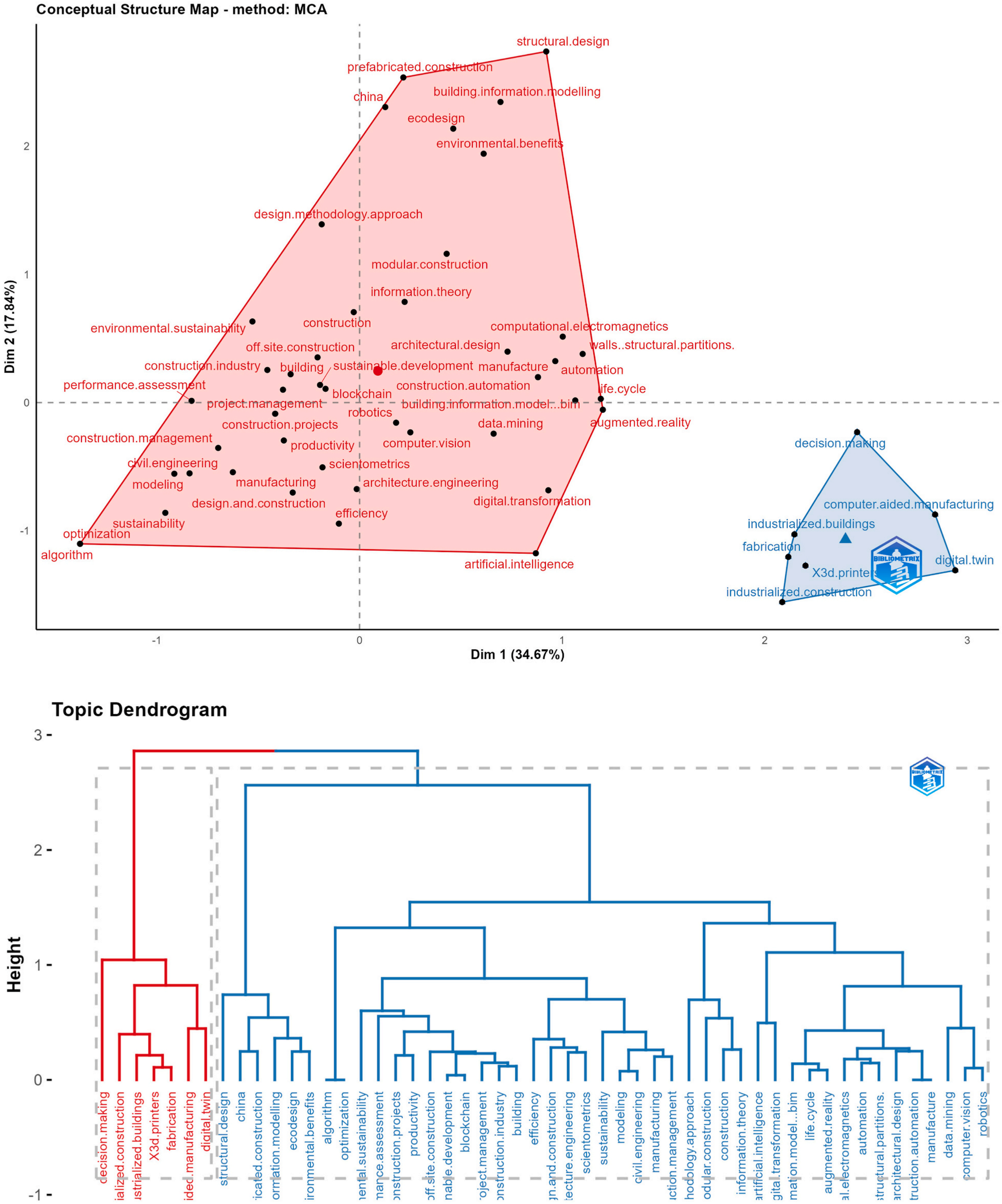


Fig. 11. Dendrogram and conceptual structure analysis for management topic.

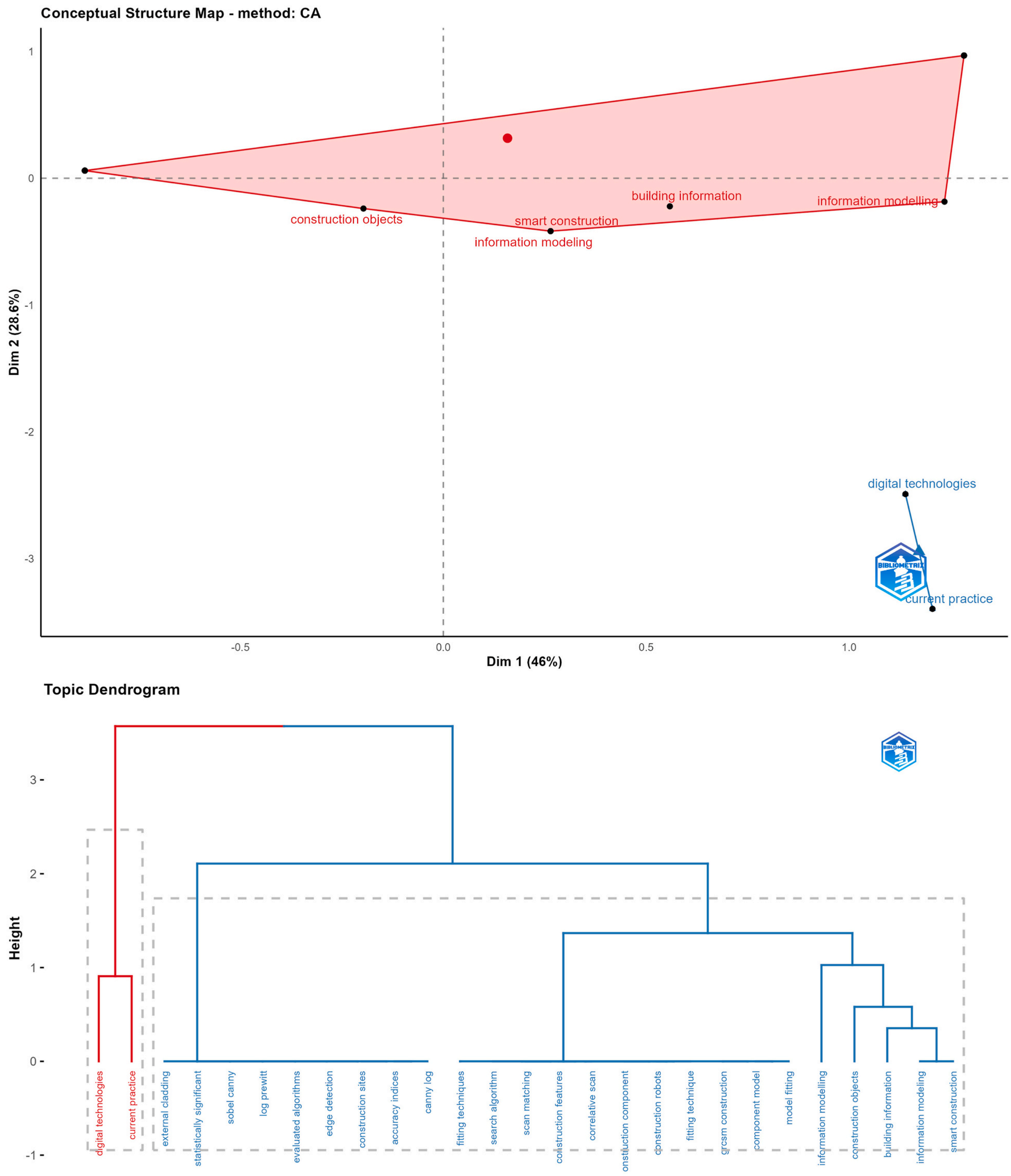


Fig. 12. Dendrogram and conceptual structure analysis for industry 4.0 topic.

6.2. *Future directions*

With the results obtained in Section 6.1, mainly through the allocation of the analyzed documents to various clusters as shown in Fig. 9, this section delves into the subjects of sustainability and green building (Fig. 10), industry management (Fig. 11), and Industry 4.0 (Fig. 12) to identify future trends in each topic. The analysis will be conducted using conceptual structure maps and multi-dimensional scaling (MDS) with topic dendrogram charts to discern the dominant concepts and their relationship.

In Fig. 10, the relationships between articles and key concepts are depicted. The four main concepts are environmental impact, urban planning, life cycle, and green building. A conceptual structure map reveals three prominent themes. The first green theme focuses on eco-friendly construction materials, mainly rubber. The second theme, in red, pertains to assessing environmental impact, urban planning, and sustainable city development. The final theme, in blue, highlights the connection between manufacturing processes, life cycle analysis, and the impact of industrialized construction on the environment. The dendrogram shows that all aspects of urban development are closely related to energy development, manufacturing processes, life cycle analysis, and developing innovative materials for green building.

MMCs have the advantage of allowing for the early selection of materials and construction methods. While any material can be used, those that facilitate integration and have "dry joint" components are preferred for a cleaner construction process. Lightweight materials are also favored for ease of transportation and assembly. One of the most significant advantages of many MMC-based single-family homes is the ease of assembly and disassembly. Using recyclable, sustainable and eco-friendly materials further reduces the environmental impact [160]. The choice of MMCs also extends beyond traditional building components to include new materials such as biodegradable bioplastics, 3D printed materials, nanomaterials, eco-friendly concrete, and smart glass for energy collection and protection.

Several key technologies can be implemented to enhance the sustainability of new buildings, such as green and sustainable building materials, renewable energy sources like solar panels and wind turbines, LED lighting, sustainable drainage systems, thermal insulation materials, and sensor and automation systems. Adopting these technologies can effectively reduce the carbon footprint of the building, minimize energy consumption, and reduce the usage of non-renewable resources while generating significant cost savings and improving water quality [128]. Furthermore, these solutions can enhance building efficiency and provide occupants with a higher quality of life.

However, the current sustainability paradigm is no longer sufficient in reducing the environmental impacts of human activity [136]. It is necessary to consider economic and social aspects to achieve a balance, but this is complex as environmental, social, and economic sustainability may not always be compatible [17]. For instance, a faster construction method reduces transportation requirements for workers, resulting in reduced energy consumption and improved environmental performance. The challenge is to preserve natural resources, heritage, culture, social balance, and ecosystems for future generations.

To address this challenge, the old "recycle, reduce, and reuse" approach must be replaced by "restore, renew, and replace" [179]. The new paradigm, Regenerative Design, aims to generate positive impacts throughout the entire life cycle of buildings by restoring and developing natural and human ecosystems. This requires a shift in thinking and design with a holistic and integrated approach incorporating a high scientific knowledge level. The shift to Regenerative Design requires in-depth knowledge of various areas. It may require the collaboration of several specialists, appropriate tools, and new research methods, guidelines, and design strategies. MMCs are an approach that uses innovative technologies and processes to improve the efficiency and quality of construction [29]. This includes prefabrication of components, using lighter and stronger materials, and faster and more precise construction techniques related to regenerative design.

By employing more sustainable materials, reducing construction waste, and lowering the carbon footprint, MMCs can create more sustainable and efficient buildings and communities that promote environmental regeneration and community health. This represents a paradigm shift towards more sustainable and environmentally responsible practices in the built environment that will need the full attention of the scientific community within a few years.

Fig. 11 displays the visualizations for the management-related clusters. The conceptual structure map reveals two main groups, depicted as two lines. The first group, shown in blue, highlights the management of industrialized processes, focusing on 3D printing, digital twins, and computer-aided manufacturing. The second group, shown in red, pertains to automation and project management and incorporates digital technologies [26] such as BIM, robotics, computer vision, data mining, and augmented reality. The largest group in the dendrogram is related to structural eco-design and is closely tied to prefabricated construction in China [145]. On the other hand, all the automation and efficiency elements are connected to technology integration. The potential of applying technologies such as extended reality, Big Data, and 3DP in industrialized construction still needs to be explored [125]. Through the integration of on-site construction robots and 3D printing technology, the field of architecture is poised to experience a wave of innovation, particularly in the areas of design and building materials, ushering in a new era of construction [27].

However, the application of these technologies in the context of MMCs in architecture is often limited to new construction projects [29]. Although the use of industrialized building techniques is becoming more accepted in the construction of new housing, it is still rare in the context of building rehabilitation. The limited research in this field is a hindrance to the implementation of MMCs in retrofitting, which is becoming increasingly necessary. The construction industry is a significant contributor to energy consumption, accounting for around 40% of final energy use in the European Union. This highlights the need for energy-efficient renovations of existing buildings. Innovative and unconventional approaches are necessary to enhance energy efficiency, particularly in existing buildings, significantly. AI offers a solution that can automatically achieve this goal without imposing a significant burden on building operators and owners [113].

Construction 4.0 faces two challenges: the urgent need for energy-efficient retrofits of large building envelopes and the cost-effectiveness of such projects. MMCs, in conjunction with building mapping and management technologies such as BIM and drones, would significantly accelerate progress toward meeting these needs.

Fig. 12 displays the results of the cluster analysis and dendrograms related to Industry 4.0. Two distinct groups are identified in the cluster. The first group focuses on the Internet of Things and BIM, which work together to achieve control and operational efficiency. BIM allows for planning and updates, and sensors provide real-time monitoring, enabling the application of analytics. BIM has its roots in the 1960s with Sketchpad, a primary application allowing users to manipulate objects on a computer screen. BIM precursor applications were first used on personal computers in the mid-1980s for large projects like the Heathrow Airport terminal renovation. Modern BIM design emerged in the late 1990s and early 2000s [6]. The second group, as seen in the dendrogram, highlights the technology and techniques used, focusing on integrating robots, construction equipment, algorithms for statistical analysis and AI. Predictive tasks in AI and ML-driven analytics rely on historical data sets to make accurate predictions about new observations [77]. The field of ML has a history that predates BIM, going back to the year 1950 when Alan Turing created the "Turing Test". This test required a machine to deceive a human into believing that they were interacting with another human instead of a computer.

Key technologies, such as those mentioned above, include complete automation of the entire project lifecycle. Moreover, these technologies will facilitate significant changes in OSC operations by 2030, including the transition from single-product manufacturing to modularization, a shift from customized offsite building components to standardized ones, a move away from permanent offsite building structures to relocatable or portable ones, and a shift from dependence on single-skilled labor to multi-skilled labor [28]. Buildings constructed using MMC systems today are complex, involving advanced architectural, structural, and mechanical engineering systems that play a role throughout the building's life cycle. Further research is needed to understand the interdependent building systems through the use of digital twins. There is also a significant opportunity to delve deeper into the social impacts of these buildings, which have yet to be fully explored, to optimize their sustainability performance from a holistic perspective.

7. Conclusions

This article studies MMCs in building construction. The study was based on a comprehensive review of the literature published in the past 47 years, extracted from the Scopus database. The research was conducted in three phases: (1) Historical review and classification of MMCs: The article provides an overview of the history of industrialized construction and clarifies commonly misunderstood terminologies. A revised classification of MMCs was developed, grouping them into six categories, ranging from off-site manufacturing and prefabrication to process improvement and technology applications. (2) Quantitative analysis of literature: The study analyzed 633 articles from the literature using Natural Language Processing (NLP) analysis. (3) Qualitative analysis through Systematic Literature Review (SLR): A sample of 180 selected articles was subjected to a qualitative analysis using SLR. The research methodology combined traditional expert knowledge with modern machine learning (ML) techniques. A pre-trained BERT model, UMAP feature reduction method, and hierarchical clustering algorithm were used to extract the relevant themes from the literature. The results were filtered through keywords and visualized using the R package bibliometrix and VOSviewer.

The scientometric assessment provides a statistical overview of the current state of the MMC field. The assessment includes an analysis of the annual production, most influential sources, authors, international collaboration, and highly referenced articles. The results of the quantitative analysis revealed that the increasing demand for MMCs in recent years, driven by new building requirements and technological advancements in construction 4.0, has led to a marked increase in research and literature production, with a significant increase observed from 2017 onwards. The analysis shows that 50% of the literature on MMCs was generated in only four countries: the United Kingdom, followed by Australia, the USA, and China. Through bibliometric analysis and scientific mapping tools, the study identified and synthesized the significant themes in MMC research, grouping them into six categories: Construction 4.0, Sustainable Construction, Emerging Markets, Decision Analysis, Green Building, and Industry Management. A qualitative analysis was then performed to delve into the research gaps and trends in MMC research, identifying 18 subcategories of the six main themes.

The speed of delivery, the ability to make up for lost time, and the opportunity to maintain high productivity while implementing social distancing in construction are key factors driving the shift towards MMCs over conventional methods. Implementing efficient construction practices such as reducing material waste can also help mitigate potential increases in material costs due to shortages, thus offsetting the cost differential between MMCs and traditional construction methods. Traditional construction methods are labor-intensive, making creating a suitable working environment challenging. However, off-site construction requires less concentration of labor, which facilitates the creation of safer spaces. MMCs can improve safety, quality, and time efficiency while minimizing waste. It is concluded that in the short term, labor shortages and the need to increase the housing supply will be the main drivers of MMC adoption in specific markets, as is already the case in Asia. In the medium to long term, the environmental impact of construction will require the widespread adoption of MMCs worldwide.

The predominant research trends in construction are focused on applying tools and technologies associated with Construction 4.0. These include the Building Information Modelling (BIM) methodology, process automation, Big Data analysis, cloud technologies, and the Internet of Things, collectively contributing to accelerating the building process from the early design phase. While MMCs are often presented as an ideal solution to meet the housing needs of modern society, research gaps demonstrate the need to focus more on industrialized retrofitting, which has enormous potential to improve the existing huge housing stock. These gaps highlight the need for further research into how MMCs can be utilized to retrofit and revitalize existing structures effectively. At last, the great challenge for future research will be addressing the sustainability paradigm crisis and shifting toward a regenerative design model. In this regard, MMCs will play a crucial role in promoting environmental regeneration and community health by reducing waste and carbon emissions, enhancing energy efficiency, and enabling the development of sustainable communities.

The key findings of this research can be summarized into three main points: (1) A revised classification system for Modern Methods of Construction (MMC) used in building construction, particularly in housing. This system makes it easier for researchers to access bibliographic information and keeps pace with the inclusion of new construction systems as they emerge. (2) The establishment of a multi-hierarchical knowledge structure consisting of central themes in MMC research topics, providing updated references for researchers and industry stakeholders. (3) A discussion on the cutting-edge MMC markets, focusing on construction technology 4.0 and industry management while keeping sustainability at the forefront and providing suggestions for future lines of research to address existing knowledge gaps. In summary, MMCs offer a promising solution to the building sector's low productivity, labor shortages, and cost control issues while reducing uncertainty, minimizing waste, and promoting sustainability. However, this study is limited to analyzing English language articles in Scopus and JCR journals. Future research could expand to include conference papers and further explore the effects of keyword co-occurrence and qualitative analysis through dendrogram analysis.

The results of this study are distinguished from previous reviews by their comprehensive approach and methodology. It covers a broader range of MMCs, introduces a more accurate classification system than its predecessors, provides in-depth analysis, identifies previously unexplored research gaps, and offers roadmaps to facilitate the application of these models.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Grant PID2020-117056RB-I00 funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”.

References

[1] A.A. Alhusban, S.A. Alhusban, M.A. Alhusban, How the COVID 19 pandemic would change the future of architectural design, J. Eng. Des. Technol. 20 (1) (2022) 339–357, https://doi.org/10.1108/JEDT-03-2021-0148.

[2] G. Tokazhanov, A. Tleuken, M. Guney, A. Turkyilmaz, F. Karaca, How is COVID-19 experience transforming sustainability requirements of residential buildings? A review, Sustainability 12 (2020) 8732, https://doi.org/10.3390/su12208732.

[3] F. Colangelo, A. Petrillo, I. Farina, Comparative environmental evaluation of recycled aggregates from construction and demolition wastes in Italy, Sci. Total Environ. 798 (2021), 149250, https://doi.org/10.1016/j.scitotenv.2021.149250.

[4] P. Dallasega, E. Rauch, C. Linder, Industry 4.0 as an enabler of proximity for construction supply chains: a systematic literature review, Comput. Ind. 99 (2018) 205–225, https://doi.org/10.1016/j.compind.2018.03.039.

[5] M.M. Tjebane, I. Musonda, C. Okoro, A. Onososen, Artificial intelligence (AI) in sustainable construction management: a scientometric review, in: T.C. Haupt, M. Akinlolu, F. Simpeh, C. Amoah, Z. Armoed (Eds.), Construction in 5D: Deconstruction, Digitalization, Disruption, Disaster, Development, Lecture Notes in Civil Engineering, vol. 245, Springer, Cham, 2023, https://doi.org/10.1007/978-3-030-97748-1_12.

[6] X. Yin, H. Liu, Y. Chen, M. Al-Hussein, Building information modelling for off-site construction: review and future directions, Autom. ConStruct. 101 (2019) 72–91, https://doi.org/10.1016/j.autcon.2019.01.010.

[7] W. Pan, A.G.F. Gibb, A.R.J. Dainty, Perspectives of U.K. housebuilders on the use of offsite modern methods of construction, Construct. Manag. Econ. 25 (2) (2007) 183–194, https://doi.org/10.1080/01446190600827058.

[8] M.M. Rahman, Barriers of implementing modern methods of construction, J. Manag. Eng. 30 (1) (2014) 69–77, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000173.

[9] I.L. Jabar, F. Ismail, A.A. Mustafa, Issues in managing construction phase of IBS projects, Procedia Social and Behavioral Sciences 101 (2013) 81–89, https://doi.org/10.1016/j.sbspro.2013.07.181.

[10] T. Li, L.-M. Yuan, G.-Q. Hou, Y.-F. Wu, Rapid design and construction management of emergency hospital during the COVID-19 epidemic, Struct. Eng. Int. 32 (2) (2022) 142–146, https://doi.org/10.1080/10168664.2021.1955087.

[11] Town and Country Planning Association, Guide 12: Modern Methods of Construction, in: Practical Guides for Creating Successful New Communities, TCPA, published April 2020, (Accessed 23 August 2022). https://tcpa.org.uk/resources/guide-12-modern-methods-of-construction/.

[12] E. Pellicer, V. Yepes, C.L. Correa, L.F. Alarcón, Model for systematic innovation in construction companies, J. Construct. Eng. Manag. 140 (4) (2014) B4014001, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000700.

[13] Platform for Housing Industrialization (PIV – Plataforma para la Industrialización de Viviendas, in Spanish), published on October 13, 2020, https://www.construible.es/2020/10/13/plataforma-industrializacion-viviendas-impulsara-construccion. (Accessed 23 August 2022).

[14] S. Navaratnam, T. Ngo, T. Gunawardena, D. Henderson, Performance review of prefabricated building systems and future research in Australia, Buildings 9 (2) (2019) 38, https://doi.org/10.3390/buildings9020038.

[15] R. Dowsett, M. Green, M. Sexton, C. Harty, Projecting at the project level: MMC supply chain integration roadmap for small housebuilders, Construct. Innovat. 19 (2) (2019) 193–211, https://doi.org/10.1108/CI-07-2017-0059.

[16] J. Hong, G.Q. Shen, Z. Li, B. Zhang, W. Zhang, Barriers to promoting prefabricated construction in China: a cost–benefit analysis, J. Clean. Prod. 172 (2018) 649–660, https://doi.org/10.1016/j.jclepro.2017.10.171.

[17] M. Kamali, K. Hewage, Life cycle performance of modular buildings: a critical review, Renew. Sustain. Energy Rev. 62 (2016) 1171–1183, https://doi.org/10.1016/j.rser.2016.05.031.

[18] Y. Yu, Z. Chen, A. Chen, Experimental study of a pretensioned connection for modular buildings, Steel Compos. Struct. 31 (3) (2019) 217–232, https://doi.org/10.12989/scs.2019.31.3.217.

[19] I.J. Navarro, V. Yepes, J.V. Martí, F. González-Vidosa, Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks, J. Clean. Prod. 196 (2018) 698–713, https://doi.org/10.1016/j.jclepro.2018.06.110.

[20] J.T. O’Connor, W.J. O’Brien, J.O. Choi, Critical success factors and enablers for optimum and maximum industrial modularization, J. Construct. Eng. Manag. 140 (6) (2014), https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842.

[21] A.A. Rahim, S.L. Qureshi, A review of IBS implementation in Malaysia and Singapore, Plann. Malays. 16 (2) (2018) 323–333, https://doi.org/10.21837/pm.v16i6.486.

[22] F.E. Boafo, J.H. Kim, J.T. Kim, Performance of modular prefabricated architecture: case study-based review and future pathways, Sustainability 8 (6) (2016) 558, https://doi.org/10.3390/su8060558.

[23] R. Jin, S. Gao, A. Cheshmehzangi, E. Aboagye-Nimo, A holistic review of offsite construction literature published between 2008 and 2018, J. Clean. Prod. 202 (2018) 1202–1219, https://doi.org/10.1016/j.jclepro.2018.

[24] S. Gao, R. Jin, W. Lu, Design for manufacture and assembly in construction: a review, Build. Res. Inf. 48 (5) (2019) 538–550, https://doi.org/10.1080/09613218.2019.1660608.

[25] M.N.A. Azman, M.S.S. Ahamad, T.A. Majid, M.H. Hanafi, Status of industrialized building system manufacturing plant in Malaysia, JCEST 2 (2) (2011), https://doi.org/10.33736/jcest.89.2011.

[26] M. Wang, C.C. Wang, S. Sepasgozar, S.A. Zlatanova, A systematic review of digital technology adoption in off-site construction: current status and future direction towards industry 4.0, Buildings 10 (11) (2020) 204, https://doi.org/10.3390/buildings10110204.

[27] M. Gharbia, A. Chang-Richards, Y. Lu, R.Y. Zhong, H. Li, Robotic technologies for on-site building construction: a systematic review, J. Build. Eng. 32 (2020), 101584, https://doi.org/10.1016/j.jobe.2020.101584.

[28] R.H. Assaad, I.H. El-Adaway, M. Hastak, K. Lascola Needy, Quantification of the state of practice of offsite construction and related technologies: current trends and future prospects, J. Construct. Eng. Manag. 148 (7) (2022), 4022055, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002302.

[29] B. Qi, M. Razkenari, A. Costin, C. Kibert, M. Fu, A systematic review of emerging technologies in industrialized construction, J. Build. Eng. 39 (2021), 102265, https://doi.org/10.1016/j.jobe.2021.102265.

[30] C. Davies, The Prefabricated Home, Reaktion books, Trowbridge, 2005. https://pdfslide.net/download/link/prefabricatedhomepdf. (Accessed 17 September 2022).

[31] M.D. Taylor, A definition and valuation of the UK offsite construction sector, Construct. Manag. Econ. 28 (8) (2010) 885–896, https://doi.org/10.1080/01446193.2010.480976.

[32] B. Bergdoll, P. Christensen, Home Delivery: Fabricating the Modern Dwelling, New York Museum of Modern Art, Basel Birkhäuser, 2008.

[33] E. Hofman, H. Voordijk, J. Halman, Matching supply networks to a modular product architecture in the house-building industry, Build. Res. Inf. 37 (1) (2009) 31–42, https://doi.org/10.1080/09613210802628003.

[34] G. Staib, A. Dörrhöfer, M. Rosenthal, Components and Systems. Modular Construction: Design, Structure, New Technologies, Birkhäuser-Detail, Berlin, 2008, 978-3-7643-8656-6.

[35] G. Wadel, La sostenibilidad en la arquitectura industrializada: la construcción modular ligera aplicada a la vivienda, PhD thesis. Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, 18-11, https://dialnet.unirioja.es/servlet/tesis?codigo=83647, 2009.

[36] B. Burkhart, A. Arieff, Prefab., Gibbs Smith, Layton, Utah, U.S.A., 2002. ISBN 10: 1586851322.

[37] E. Attouri, Z. Lafhaj, L. Ducoulombier, B. Linéatte, The current use of industrialized construction techniques in France: benefits, limits and future expectations, Clean. Eng. Technol. 8 (2022), 100454, https://doi.org/10.1016/j.clet.2022.100436.

[38] S. Burwood, P. Jess, Modern Methods of Construction Evolution or Revolution? A BURA Steering and Development Forum Report, 2005.

[39] A. Gibb, M. Pendlebury, Glossary of Term Buildoffsite UK, Buildoffsite, 2005. Update 2013, https://www.buildoffsite.com/content/uploads/2015/03/BoS-Glossary-of-terms-2013-web.pdf. (Accessed 16 September 2022).

[40] NHBC Foundation, A Guide to Modern Methods of Construction (MMC), 2007. https://www.nhbcfoundation.org/publication/a-guide-to-modern-methods-of-construction/. (Accessed 16 September 2022).

[41] K.A. Kamar, Z.A. Hamid, M.N. Azman, M.S. Ahamad, Industrialized building system (IBS): revisiting issues of definition and classification, Int. J. Emerg. Sci. 1 (2011) 120–132. ISSN: 2222-4254.

[42] I.E. Majzub, Modular housing systems used around the world, Int. J. of. Hous. Sci 1 (1977) 73–84.

[43] Y.F. Badir, M.R.A. Kadir, A.A.A. Ali, Theory of Classification of Badir- Razali Building System Classification, Buletin of Institution of Engineer, Malaysia, 1998.

[44] A. Warszawski, Industrialized and Automated Building System, second ed., Technion- Israel Institute of Technology: E & FN SPON, 1999 https://doi.org/10.4324/9780203223697.

[45] Y.F. Badir, M.R.A. Kadir, A.H. Hashim, Industrialized building systems construction in Malaysia, J. Architect. Eng. 8 (1) (2002) 19–23, https://doi.org/10.1061/(ASCE)1076-0431(2002)8:1(19).

[46] A. Gibb, F. Isack, Re-engineering through pre-assembly: client expectations and drivers, Build. Res. Inf. 31 (2) (2003) 146–160, https://doi.org/10.1080/09613210302000.

[47] S.N. Shaari, E. Ismail, Promoting the Usage of Industrialized Building System (IBS) and Modular Coordination (MC) in Malaysian Construction Industry, vols. 1–5, Board of Engineers Magazine, 2003, 2003.

[48] A.B. Rahman, W. Omar, Issues and challenges in the implementation of IBS in Malaysia, in: 6th Asia-Pacific Structural Engineering and Construction Conference (ASPEC 2006), 2006.

[49] R.B. Richard, A generic classification of industrialized building system in open building manufacturing- core concept and industrial requirement, Open Building Manufacturing: Core Concepts and Industrial Requirements 2007 (2007) 33–48.

[50] H. Abosoad, J. Underwood, S. Boreny, Towards an Information System Representation of OSM in Facilitating the Virtual Prototyping of Housing Design, BuHu 9th International Postgraduate Research Conference (IPGRC), 2009, pp. 509–520.

[51] N. Lu, in: S.T. Ariaratnam, E.M. Rojas (Eds.), The Current Use of Offsite Construction Techniques in the United States Construction Industry, Seattle, Washington. ASCE, 2009, https://doi.org/10.1061/41020(339)96, 96-96.

[52] N. Blismas, R. Wakefield, Drivers, constraints and the future of offsite manufacture in Australia, Construct. Innovat. 9 (1) (2009) 72–83, https://doi.org/10.1108/14714170910931552.

[53] CIDB, The current state of industrialised building system (IBS) construction forward, in: Proceedings of the 1st IBS Roundtable Workshop, 2011. Kuala Lumpur.

[54] D. Doran, M. Giannakis, An examination of a modular supply chain: a construction sector perspective, Supply Chain Manag. 16 (4) (2011) 260–270, https://doi.org/10.1108/13598541111139071.

[55] P. Mesároš, T. Mandičák, Factors affecting the use of modern methods and materials in construction, IOP Conf. Ser. Mater. Sci. Eng. 71 (2015), 12053.

[56] H. Khan, M.Z. Khan, Modern methods of construction, IJARIIE 5 (4) (2019) 203–230. IJARIIE-ISSN(O)-2395-4396.

[57] A. Harden, J. Thomas, Mixed Methods and Systematic Reviews: Examples and Emerging Issues, SAGE Handbook of Mixed Methods in Social & Behavioral Research, 2010, pp. 749–774, https://doi.org/10.4135/9781506335193.

[58] J. Devlin, M. Chang, K. Lee, K. Toutanova, Bert: Pre-training of Deep Bidirectional Transformers for Language Understanding, 2018 arXiv preprint arXiv:1810.04805.

[59] R. Bro, A. Smilde, Principal component analysis, Anal. Methods 6 (2014) 2812–2831, https://doi.org/10.1039/C3AY41907J.

[60] J. Garcia, G. Villavicencio, F. Altimiras, B. Crawford, R. Soto, V. Minatogawa, M. Franco, D. Martinez-Munoz, V. Yepes, Machine learning techniques applied to construction: a hybrid bibliometric analysis of advances and future directions, Autom. ConStruct. 142 (2022), 104532, https://doi.org/10.1016/j.autcon.2022.104532.

[61] L. McInnes, J. Healy, J. Melville, Umap: Uniform Manifold Approximation and Projection for Dimension Reduction, 2018. ArXiv Preprint arXiv:1802.03426.

[62] M. Grootendorst, BERTopic: Neural Topic Modeling with a Class-Based TF-IDF Procedure, 2022 arXiv preprint arXiv:2203.05794.

[63] R. Campello, D. Moulavi, J. Sander, Density-based clustering based on hierarchical density estimates, in: Pacific-asia Conference on Knowledge Discovery and Data Mining, 2013, pp. 160–172, https://doi.org/10.1007/978-3-642-37456-2_14.

[64] D. Blei, A. Ng, M. Jordan, Latent dirichlet allocation, J. Mach. Learn. Res. 3 (2003) 993–1022, https://doi.org/10.5555/944919.944937.

[65] M. Aria, C. Cuccurullo, Bibliometrix: an R-tool for comprehensive science mapping analysis, J. Informetr. 11 (2017) 959–975, https://doi.org/10.1016/j.joi.2017.08.007.

[66] L. Grivel, P. Mutschke, X. Polanco, Thematic mapping on bibliographic databases by cluster analysis: a description of the sdoc environment with solis, J. Knowl. Organ. 22 (1995) 70–77, https://doi.org/10.5771/0943-7444-1995-2.

[67] M. López-Fernández, A. Serrano-Bedia, M. Pérez-Pérez, Entrepreneurship and family firm research: a bibliometric analysis of an emerging field, J. Small Bus. Manag. 54 (2016) 622–639, https://doi.org/10.1111/jsbm.12161.

[68] T.K. Landauer, P.W. Foltz, D. Laham, An introduction to latent semantic analysis, Discourse Process 25 (2–3) (1998) 259–284, https://doi.org/10.1080/01638539809545028.

[69] Y. Wang, H. Bai, M. Stanton, W.Y. Chen, E.Y. Chang, PLDA: parallel latent dirichlet allocation for large-scale applications, AAIM 2009, in: Algorithmic Aspects in Information and Management: 5th International Conference, Springer Berlin Heidelberg, San Francisco, CA, USA, 2009, pp. 301–314. June 15-17, 2009. Proceedings 5, https://link.springer.com/chapter/10.1007/978-3-642-02158-9_26.

[70] D.D. Lee, H.S. Seung, Learning the parts of objects by non-negative matrix factorization, Nature 401 (6755) (1999) 788–791, https://doi.org/10.1038/44565.

[71] W. Li, A. McCallum, Pachinko allocation: DAG-structured mixture models of topic correlations, in: Proceedings of the 23rd International Conference on Machine Learning, 2006, pp. 577–584. https://people.cs.umass.edu/~mccallum/papers/pam-icml06.pdf.

[72] A.M.T. Thome, L.F. Scavarda, A.J. Scavarda, Conducting systematic literature review in operations management, Prod. Plann. Control 27 (5) (2016) 408–420, https://doi.org/10.1080/09537287.2015.1129464.

[73] D. Moher, L. Shamseer, M. Clarke, D. Ghersi, A. Liberati, M. Petticrew, P. Shekelle, L.A. Stewart, PRISMA-P Group, Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement, Syst. Rev. 4 (1) (2015), https://doi.org/10.1186/2046-4053-4-1.

[74] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, D. Moher, Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement, J. Clin. Epidemiol. 134 (2021) 103–112, https://doi.org/10.1016/j.jclinepi.2021.02.003.

[75] A. Aghaei Chadegani, H. Salehi, M.M. Md Yunus, H. Farhadi, M. Fooladi, M. Farhadi, N. Ale Ebrahim, A comparison between two main academic literature collections: web of science and scopus databases, Asian Soc. Sci. 9 (5) (2013) 18–26, https://doi.org/10.5539/ass.v9n5p18.

[76] P. Mongeon, A. Paul-Hus, The journal coverage of Web of Science and Scopus: a comparative analysis, Scientometrics 106 (1) (2016) 213–228, https://doi.org/10.1007/s11192-015-1765-5, 2016.

[77] Y. Pan, L. Zhang, Roles of artificial intelligence in construction engineering and management: a critical review and future trends, Autom. ConStruct. 122 (2021), 103517, https://doi.org/10.1016/j.autcon.2020.103517.

[78] A.J. Sánchez-Garrido, I.J. Navarro, V. Yepes, Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction, J. Clean. Prod. 330 (2022), 129724, https://doi.org/10.1016/j.jclepro.2021.129724.

[79] W. Pan, A.G.F. Gibbs, A.R.J. Dainty, Leading UK housebuilders' utilization of offsite construction methods, Build. Res. Inf. 36 (1) (2008) 56–67, https://doi.org/10.1080/09613210701204013.

[80] A. Darko, A.P.C. Chan, M.A. Adabre, D.J. Edwards, M.R. Hosseini, E.E. Ameyaw, Artificial intelligence in the AEC industry: scientometric analysis and visualization of research activities, Autom. ConStruct. 112 (2020), 103081, https://doi.org/10.1016/j.autcon.2020.103081.

[81] X. Zhang, M. Skitmore, Exploring the challenges to industrialized residential building in China, Habitat Int. 41 (2014) 176–184, https://doi.org/10.1016/j.habitatint.2013.08.005.

[82] Z. Liz, G.Q. Shen, M. Alshawi, Measuring the impact of prefabrication on construction waste reduction: an empirical study in China, Resour. Conserv. Recycl. 91 (2014) 27–39, https://doi.org/10.1016/j.resconrec.2014.07.013.

[83] C. Mao, F. Xie, L. Hou, P. Wu, J. Wang, X. Wang, Cost analysis for sustainable off-site construction based on a multiple-case study in China, Habitat Int. 57 (2016) 215–222, https://doi.org/10.1016/j.habitatint.2016.08.002.

[84] Y.M. Ibrahim, T.C. Lukins, X. Zhang, E. Trucco, A.P. Kaka, Towards automated progress assessment of workpackage components in construction projects using computer vision, Adv. Eng. Inf. 23 (1) (2009) 93–103, https://doi.org/10.1016/j.aei.2008.07.002.

[85] J. Willmann, M. Knauss, T. Bonwetsch, A.A. Apolinarska, F. Gramazio, M. Kohler, Robotic timber construction — expanding additive fabrication to new dimensions, Autom. ConStruct. 61 (2016) 16–23, https://doi.org/10.1016/j.autcon.2015.09.011.

[86] H. Yu, M. Al-Hussein, S. Al-Jibouri A. Telyas, Lean transformation in a modular building company: a case for implementation, J. Manag. Eng. 29 (1) (2013) 103–111, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000115.

[87] W. Pan, A.R.J. Dainty, A.G.F. Gibbs, Establishing and weighting decision criteria for building system selection in housing construction, J. Construct. Eng. Manag. 138 (11) (2012) 1239–1250, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000543.

[88] X. Liu, M.A. Bradford, Behavior of high-strength friction-grip bolted shear connectors in sustainable composite beams, J. Struct. Eng. 141 (6) (2015), 4014149, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001090.

[89] Y. Niu, W. Lu, K. Chen, G.G. Huang, Smart construction objects, J. Comput. Civ. Eng. 30(4) 4015070, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000550.

[90] M. Pan, T. Linner, W. Pan, h. cheng, T. Bock, A framework of indicators for assessing construction automation and robotics in the sustainability context, J. Clean. Prod. 182 (2018) 82–95, https://doi.org/10.1016/j.jclepro.2018.02.053.

[91] X. Li, G.Q. Shen, P. Wu, H. Fang, RBL-PHP: simulation of lean construction and information technologies for prefabrication housing production, J. Manag. Eng. 34 (2) (2018), 4017053, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000577.

[92] T. Linner, T. Bock, Evolution of large-scale industrialisation and service innovation in Japanese prefabrication industry, Construct. Innovat. 12 (2) (2012) 156–178, https://doi.org/10.1108/14714171211215921.

[93] Y. Teng, C. Mao, G. Liu, X. Wang, Analysis of stakeholder relationships in the industry chain of industrialized building in China, J. Clean. Prod. 152 (2017) 387–398, https://doi.org/10.1016/j.jclepro.2017.03.094.

[94] X. Liu, M.A. Bradford, A. Ataei, Flexural performance of innovative sustainable composite steel-concrete beams, Eng. Struct. 130 (2017) 282–296, https://doi.org/10.1016/j.engstruct.2016.10.009.

[95] P. Martinez, H. Al-Hussein, R. Ahmad, A scientometric analysis and critical review of computer vision applications for construction, Autom. ConStruct. 107 (2019), 102947, https://doi.org/10.1016/j.autcon.2019.102947.

[96] M. Sedighi, Application of word co-occurrence analysis method in mapping of the scientific fields (case study: the field of Informetrics), Libr. Rev. 65 (1/2) (2016) 52–64, https://doi.org/10.1108/LR-07-2015-0075.

[97] N.J. Van Eck, L. Waltman, Manual for VOSviewer Version 1.6.18, 2022 published on January 24, https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.18.pdf.

[98] O. Persson, R. Danell, J.W. Schneider, How to use Bibexcel for various types of bibliometric analysis, in: F. Åström, R. Danell, B. Larsen, J. Schneider (Eds.), Celebrating Scholarly Communication Studies: A Festschrift for Olle Persson at His 60th Birthday, International Society for Scientometrics and Informetrics, Leuven, Belgium, 2009, pp. 9–24. http://homepage.univie.ac.at/juan.gorraiz/bibexcel/.

[99] F. Herkommer, B. Bley, CAD/CAM for the prefabrication of brickwork, Autom. ConStruct. 4 (4) (1996) 321–329, https://doi.org/10.1016/0926-5805(95)00013-5.

[100] R. Yin, Y. Zou, K. Gidado, P. Ashton, N. Painting, Scientometric analysis of BIM-based research in construction engineering and management, Eng. Construct. Architect. Manag. 26 (8) (2019) 1750–1776, https://doi.org/10.1108/ECAM-08-2018-0350.

[101] S. Abrishami, R. Martín-Durán, BIM and DfMA: a paradigm of new opportunities, Sustainability 13 (2021) 9591, https://doi.org/10.3390/su13179591.

[102] M. Tetik, A. Peltokorpi, O. Seppänen, J. Holmström, Direct digital construction: technology-based operations management practice for continuous improvement of construction industry performance, Autom. ConStruct. 107 (2019), 102910, https://doi.org/10.1016/j.autcon.2019.102910.

[103] V.J.L. Gan, BIM-based building geometric modeling and automatic generative design for sustainable offsite construction, J. Construct. Eng. Manag. 140 (10) (2022), 4022111, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002369.

[104] M. Sheikhkhoshkar, F. Pour Rahimian, M.H. Kaveh, M.R. Hosseini, D.J. Edwards, Automated planning of concrete joint layouts with 4D-BIM, Autom. ConStruct. 107 (2019), 102943, https://doi.org/10.1016/j.autcon.2019.102943.

[105] A. Alwisy, S. Bu Hamdan, B. Barkokebas, A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings, Int. J. Construct. Manage. 19 (3) (2019) 187–205, https://doi.org/10.1080/15623599.2017.1411458.

[106] J.D. Cuellar Lobo, Z. Lei, H. Liu, S.H. Han, Building information modelling- (BIM-) based generative design for drywall installation planning in prefabricated construction, Adv. Civ. Eng. 2021 (2021), 6638236, https://doi.org/10.1155/2021/6638236.

[107] J.K.-W. Wong, K.-L. Kuan, Implementing 'BEAM Plus' for BIM-based sustainability analysis, Autom. ConStruct. 44 (2014) 163–175, https://doi.org/10.1016/j.autcon.2014.04.003.

[108] S. Barg, F. Flager, M. Fischer, An analytical method to estimate the total installed cost of structural steel building frames during early design, J. Build. Eng. 15 (2018) 41–50, https://doi.org/10.1016/j.jobe.2017.10.010.

[109] T.O. Olawumi, D.W.M. Chan, S. Ojo, M.C.H. Yam, Automating the modular construction process: a review of digital technologies and future directions with blockchain technology, J. Build. Eng. 46 (2022), 103720, https://doi.org/10.1016/j.jobe.2021.103720.

[110] R. Brandín, S. Abrishami, Information traceability platforms for asset data lifecycle: blockchain-based technologies, Smart Sustainable Built Environ 10 (3) (2021) 364–386, https://doi.org/10.1108/SASBE-03-2021-0042.

[111] G.B. Ozturk, Metrics digital twin research in the AECO-FM industry, J. Build. Eng. 40 (2021), 102730, https://doi.org/10.1016/j.jobe.2021.102730.
[112] M. Wang, M.S. Altaf, M. Al-Hussein, Y. Ma, Framework for an IoT-based shop floor material management system for panelized homebuilding, Int. J. Constr. Manag. 20 (2) (2020) 130–145, https://doi.org/10.1080/15623599.2018.1484554.
[113] C. Debrah, A.P. Chan, A. Darko, Artificial intelligence in green building, Autom. ConStruct. 107 (2022), 104192, https://doi.org/10.1016/j.autcon.2022.104192.
[114] Z. Zheng, Z. Zhang, W. Pan, Virtual prototyping- and transfer learning-enabled module detection for modular integrated construction, Autom. ConStruct. 120 (2020), 103387, https://doi.org/10.1016/j.autcon.2020.103387.
[115] A. Srivastava, S. Jawaid, R. Singh, Imperative role of technology intervention and implementation for automation in the construction industry, Adv. Civ. Eng. 2022 (2022), 6716987, https://doi.org/10.1155/2022/6716987.
[116] S. Reichenbach, B. Kromoser, State of practice of automation in precast concrete production, J. Build. Eng. 43 (221) 102527. https://doi.org/10.1016/j.jobe.2021.102527.
[117] A. Kamath, R.K. Sharma, Robotics in construction: opportunities and challenges, IJRTE 8 (2 Special Issue 11) (2019) 2227–2230, https://doi.org/10.35940/ijrte.B1242.0982S1119.
[118] P. Vähä, T. Heikkilä, P. Kilpeläinen, E. Gambao, Extending automation of building construction - survey on potential sensor technologies and robotic applications, Autom. ConStruct. 36 (2013) 168–178, https://doi.org/10.1016/j.autcon.2013.08.002.
[119] S. Bechert, D. Sonntag, L. Aldinger, J. Knippers, Integrative structural design and engineering methods for segmented timber shells - BUGA Wood Pavilion, Structures 34 (2021) 4814–4833, https://doi.org/10.1016/j.istruc.2021.10.032.
[120] B. Chu, K. Jung, M.-T. Lim, D. Hong, Robot-based construction automation: an application to steel beam assembly (Part I), Autom. ConStruct. 32 (2013) 46–61, https://doi.org/10.1016/j.autcon.2012.12.016.
[121] W. Leyh, Automatic assembly of a commercial cavity block system, Autom. ConStruct. 4 (2) (1995) 147–167, https://doi.org/10.1016/0926-5805(94)00043-M.
[122] G. Pritschow, M. Dalacker, J. Kurz, Technological aspects in the development of a mobile bricklaying robot, Autom. ConStruct. 5 (1) (1996) 3–13, https://doi.org/10.1016/0926-5805(95)00015-1.
[123] A. Abou Yassin, F. Hamzeh, F. Al Sakka, Agent based modeling to optimize workflow of robotic steel and concrete 3D printers, Autom. ConStruct. 110 (2020), 103040, https://doi.org/10.1016/j.autcon.2019.103040.
[124] R. Naboni, A. Kunic, L. Breseghello, Computational design, engineering and manufacturing of a material-efficient 3D printed lattice structure, Int. J. Architect. Comput. 18 (4) (2020) 404–423, https://doi.org/10.1177/14780771209479.
[125] S.A. Khan, M. Koç, S.G. Al-Ghamdi, Sustainability assessment, potentials and challenges of 3D printed concrete structures: a systematic review for built environmental applications, J. Clean. Prod. 303 (2021), 127027, https://doi.org/10.1016/j.jclepro.2021.127027.
[126] G.K.C. Ding, Sustainable construction-The role of environmental assessment tools, J. Environ. Manag. 86 (3) (2008) 451–464, https://doi.org/10.1016/j.jenvman.2006.12.025.
[127] K. Tajs-Zielińska, B. Bochenek, Multi-domain and multi-material topology optimization in design and strengthening of innovative sustainable structures, Sustainability 13 (6) (2021) 3435, https://doi.org/10.3390/su13063435.
[128] G. Elshafei, S. Vilčeková, M. Zeleňáková, A.M. Negm, An extensive study for a wide utilization of green architecture parameters in built environment based on genetic schemes, Buildings 11 (11) (2021) 507, https://doi.org/10.3390/buildings11110507.
[129] A.H. Whitworth, K.D. Tsavdaridis, Genetic algorithm for embodied energy optimisation of steel-concrete composite beams, Sustainability 12 (8) (2020) 3102, https://doi.org/10.3390/su12083102.
[130] S.W. Choi, B.K. Oh, H.S. Park, Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings, Energy Build. 138 (2017) 612–620, https://doi.org/10.1016/j.enbuild.2016.12.095.
[131] A.J. Sánchez-Garrido, V. Yepes, Multi-criteria assessment of alternative sustainable structures for a self-promoted, single-family home, J. Clean. Prod. 258 (2020), 120556, https://doi.org/10.1016/j.jclepro.2020.120556.
[132] J.-H. Xie, Y.-C. Guo, L.-S. Liu, Z.-H. Xie, Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber, Construct. Build. Mater. 79 (2015) 263–272, https://doi.org/10.1016/j.conbuildmat.2015.01.036.
[133] K. Thirunavukkarasu, E. Kanthasamy, P. Gatheeshgar, K. Poologanathan, H. Rajanayagam, T. Suntharalingam, M. Dissanayake, Sustainable performance of a modular building system made of built-up cold-formed steel beams, Buildings 11 (10) (2021) 460, https://doi.org/10.3390/buildings11100460.
[134] P. Gallo, R. Romano, E. Belardi, Smart green prefabrication: sustainability performances of industrialized building technologies, Sustainability 13 (9) (2021) 4701, https://doi.org/10.3390/su13094701.
[135] C. Langston, W. Zhang, DfMA: towards an integrated strategy for a more productive and sustainable construction industry in Australia, Sustainability 13 (16) (2021) 9219, https://doi.org/10.3390/su13169219.
[136] X. Hu, H.-Y. Chong, Environmental sustainability of off-site manufacturing: a literature review, Eng. Construct. Architect. Manag. 28 (1) (2021) 332–350, https://doi.org/10.1108/ECAM-06-2019-0288.
[137] J. Švajlenka, M. Kozlovská, Perception of user criteria in the context of sustainability of modern methods of construction based on wood, Sustainability 10 (2) (2018) 116, https://doi.org/10.3390/su10020116.
[138] M. Hussein, A.E.E. Eltoukhy, A. Karam, I.A. Shaban, Modelling in off-site construction supply chain management: a review and future directions for sustainable modular integrated construction, J. Clean. Prod. 310 (2021), 127503, https://doi.org/10.1016/j.jclepro.2021.127503.
[139] X. Wang, Q. Du, C. Lu, J. Li, Exploration in carbon emission reduction effect of low-carbon practices in prefabricated building supply chain, J. Clean. Prod. 368 (2022), 133153, https://doi.org/10.1016/j.jclepro.2022.133153.
[140] M. Hussein, A. Darko, A.E.E. Eltoukhy, T. Zayed, Sustainable logistics planning in modular integrated construction using multimethod simulation and taguchi approach, J. Construct. Eng. Manag. 148 (6) (2022), 4022022, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002273.
[141] J.-H. Lee, J.-S. Kim, H.-J. Lee, Y.-M. Lee, H.-G. Kim, Small-scale public rental housing development using modular construction-Lessons learned from case studies in Seoul, Korea, Sustainability 11 (4) (2019) 1120, https://doi.org/10.3390/su11041120.
[142] L.S. Pheng, C.H. Beng, Promoting innovation in prefabrication for public housing: case study of Singapore, Int. J. Hous. Sci. Appl. 26 (3) (2002) 217–226. http://scholarbank.nus.edu.sg/handle/10635/45808.
[143] Y. Wang, H. Li, Z. Wu, Attitude of the Chinese public toward off-site construction: a text mining study, J. Clean. Prod. 238 (2019), 117926, https://doi.org/10.1016/j.jclepro.2019.117926.
[144] N. Sadafi, M.F.M. Zain, M. Jamil, Adaptable industrial building system: construction industry perspective, J. Architect. Eng. 18 (2) (2012) 140–147, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000075.
[145] L. Jaillon, C.-S. Poon, Design issues of using prefabrication in Hong Kong building construction, Construct. Manag. Econ. 28 (10) (2010) 1025–1042, https://doi.org/10.1080/01446193.2010.498481.
[146] W. Xing, J.L. Hao, L. Qian, V.W.Y. Tam, K.S. Sikora, Implementing lean construction techniques and management methods in Chinese projects: a case study in Suzhou, China, J. Clean. Prod. 286 (2021), 124944, https://doi.org/10.1016/j.jclepro.2020.124944.
[147] H. Xue, S. Zhang, Y. Su, Factors affecting the capital cost of prefabrication—a case study of China, Sustainability 9 (9) (2017) 1512, https://doi.org/10.3390/su9091512.
[148] S. Shan, D. Looi, Y. Cai, P. Ma, M.-T. Chen, R. Su, B. Young, W. Pan, Engineering modular integrated construction for high-rise building: a case study in Hong Kong, Proc. Inst. Civ. Eng. Civ. Eng. 172 (6) (2019) 51–57, https://doi.org/10.1680/jcien.18.00052.
[149] Z. Li, R. Zhou, M. He, X. Sun, Modern timber construction technology and engineering applications in China, Proc. Inst. Civ. Eng. Civ. Eng. 172 (5) (2019) 17–27, https://doi.org/10.1680/jcien.18.00024.
[150] C. Newton, S. Backhouse, A.A. Aibinu, B. Cleveland, R.H. Crawford, D. Holzer, P. Soccio, T. Kvan, Plug n play: future prefab for smart green schools, Buildings 8 (7) (2018) 88, https://doi.org/10.3390/buildings8070088.

[151] W. Chen, Y. Zhao, Y. Yu, K. Chen, M. Arashpour, Collaborative scheduling of on-site and off-site operations in prefabrication, Sustainability 12 (21) (2020) 9266, https://doi.org/10.3390/su12219266.
[152] A. Katebi, P. Homami, M. Najmeddin, Acceptance model of precast concrete components in building construction based on Technology Acceptance Model (TAM) and Technology, Organization, and Environment (TOE) framework, J. Build. Eng. 45 (2022), 103518, https://doi.org/10.1016/j.jobe.2021.103518.
[153] K. Zhang, J.-S. Tsai, Identification of critical factors influencing prefabricated construction quality and their mutual relationship, Sustainability 13 (19) (2021), 11081, https://doi.org/10.3390/su131911081.
[154] W. Lu, W.M.W. Lee, F. Xue, Revisiting the effects of prefabrication on construction waste minimization: a quantitative study using bigger data, Resour. Conserv. Recycl. 170 (2021), 105579, https://doi.org/10.1016/j.resconrec.2021.105579.
[155] K. Ostrowska-Wawryniuk, Prefabrication 4.0: BIM-aided design of sustainable DIY-oriented houses, Int. J. Architect. Comput. 19 (2) (2021) 142–156, https://doi.org/10.1177/14780771209664.
[156] T. Jia Wen, H. Chin Siong, Z.Z. Noor, Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: case studies of residential buildings in Iskandar Malaysia, Energy Build. 93 (2015) 295–302, https://doi.org/10.1016/j.enbuild.2014.12.002.
[157] M.K. Ansah, X. Chen, H. Yang, L. Lu, P.T.I. Lam, Developing an automated BIM-based life cycle assessment approach for modularly designed high-rise buildings, Environ. Impact Assess. Rev. 90 (2021), 106618, https://doi.org/10.1016/j.eiar.2021.106618.
[158] A.J. Sánchez-Garrido, I.J. Navarro, V. Yepes, Evaluating the sustainability of soil improvement techniques in foundation substructures, J. Clean. Prod. 351 (2022), 131463, https://doi.org/10.1016/j.jclepro.2022.131463.
[159] J. Canto-Perello, M.P. Martinez-Garcia, J. Curiel-Esparza, M. Martin-Utrillas, Implementing sustainability criteria for selecting a roof assembly typology in medium span buildings, Sustainability 7 (6) (2015), https://doi.org/10.3390/su7066854, 6854−6871.
[160] A. Balali, A. Valipour, E.K. Zavadskas, Z. Turskis, Multi-criteria ranking of green materials according to the goals of sustainable development, Sustainability 12 (22) (2020) 9482, https://doi.org/10.3390/su12229482.
[161] M. Shahpari, F.M. Saradj, M.S. Pishvaee, S. Piri, Assessing the productivity of prefabricated and in-situ construction systems using hybrid multi-criteria decision making method, J. Build. Eng. 27 (2020), 100979, https://doi.org/10.1016/j.jobe.2019.100979.
[162] S. Navaratnam, Selecting a suitable sustainable construction method for Australian high-rise building: a multi-criteria analysis, Sustainability 14 (12) (2022) 7435, https://doi.org/10.3390/su14127435.
[163] F.G. Feldmann, H. Birkel, E. Hartmann, Exploring barriers towards modular construction – a developer perspective using fuzzy DEMATEL, J. Clean. Prod. 367 (2022), 133023, https://doi.org/10.1016/j.jclepro.2022.133023.
[164] R. Yunus, J. Yang, Improving ecological performance of industrialized building systems in Malaysia, Construct. Manag. Econ. 32 (1−2) (2014) 183–195, https://doi.org/10.1080/01446193.2013.825373.
[165] H. Jonsson, M. Rudberg, Production system classification matrix: matching product standardization and production-system design, J. Construct. Eng. Manag. 141 (6) (2015), 5015004, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000965.
[166] A.J. Sánchez-Garrido, I.J. Navarro, V. Yepes, Neutrosophic multi-criteria evaluation of sustainable alternatives for the structure of single-family homes, Environ. Impact Assess. Rev. 89 (2021), 106572, https://doi.org/10.1016/j.eiar.2021.106572.
[167] A.J. Sánchez-Garrido, I.J. Navarro, J. García, V. Yepes, An adaptive ANP & ELECTRE IS-based MCDM model using quantitative variables, Mathematics 10 (12) (2022) 2009, https://doi.org/10.3390/math10122009.
[168] S. Gee, A. Brown, A mobile system for the on-site assembly of timber frame components: the development of an agile, low-cost alternative to offsite prefabrication, Sustainability 14 (2) (2022) 651, https://doi.org/10.3390/su14020651.
[169] M. Bergström, L. Stehn, Benefits and disadvantages of ERP in industrialised timber frame housing in Sweden, Construct, Manage. Econ. 23 (8) (2005) 831–838, https://doi.org/10.1080/01446190500184097.
[170] A. Jalali Yazdi, A. Ahmadian Fard Fini, P. Forsythe, Mass-customisation of cross-laminated timber wall systems at early design stages, Autom. ConStruct. 132 (2021), 103938, https://doi.org/10.1016/j.autcon.2021.103938.
[171] C. Loss, B. Davison, Innovative composite steel-timber floors with prefabricated modular components, Eng. Struct. 132 (2017) 695–713, https://doi.org/10.1016/j.engstruct.2016.11.062.
[172] R. Lorenzo, L. Mimendi, Digitisation of bamboo culms for structural applications, J. Build. Eng. 29 (2020), 101193, https://doi.org/10.1016/j.jobe.2020.101193.
[173] I. Lukacs, A. Björnfot, R. Tomasi, Strength and stiffness of cross-laminated timber (CLT) shear walls: state-of-the-art of analytical approaches, Eng. Struct. 178 (2019) 136–147, https://doi.org/10.1016/j.engstruct.2018.05.126.
[174] C. Loss, S. Pacchioli, A. Polastri, D. Casagrande, L. Pozza, Numerical study of alternative seismic-resisting systems for CLT buildings, Buildings 8 (11) (2018) 162, https://doi.org/10.3390/buildings8110162.
[175] C. Loss, M. Piazza, R. Zandonini, Connections for steel–timber hybrid prefabricated buildings. Part I: experimental tests, Construct. Build. Mater. 122 (2016) 781–795, https://doi.org/10.1016/j.conbuildmat.2015.12.002.
[176] Y. Li, W. Shan, H. Shen, Bending resistance of I-section bamboo-steel composite beams utilizing adhesive bonding, Thin-Walled Struct. 89 (2019) 17–24, https://doi.org/10.1016/j.tws.2014.12.007.
[177] M. Mahdavi, P.L. Clouston, S.R. Arwade, A low-technology approach toward fabrication of Laminated Bamboo Lumber, Construct. Build. Mater. 29 (2012) 257–262, https://doi.org/10.1016/j.conbuildmat.2011.10.046.
[178] A.K. Aagaard, N.M. Larsen, Developing a fabrication workflow for irregular sawlogs, Int. J. Architect. Comput. 18 (3) (2020) 270–283, https://doi.org/10.1177/1478077120906736.
[179] M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: a scientific evolution analysis, J. Build. Eng. 44 (2021), 102704, https://doi.org/10.1016/j.jobe.2021.102704.
[180] G.L.F. Benachio, M.D.C.D. Freitas, S.F. Tavares, Interactions between lean construction principles and circular economy practices for the construction industry, J. Construct. Eng. Manag. 147 (7) (2021), 4021068, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002082.
[181] S. Çetin, C. De Wolf, N. Bocken, Circular digital built environment: an emerging framework, Sustainability 13 (11) (2021) 6348, https://doi.org/10.3390/su13116348.
[182] V. Cascione, M. Roberts, S. Allen, B. Dams, D. Maskell, A. Shea, P. Walker, S. Emmitt, Integration of life cycle assessments (LCA) in circular bio-based wall panel design, J. Clean. Prod. 344 (2022), 130938, https://doi.org/10.1016/j.jclepro.2022.130938.
[183] F. Bamana, N. Lehoux, C. Cloutier, Simulation of a construction project: assessing impact of just-in-time and lean principles, J. Construct. Eng. Manag. 145 (5) (2019), 5019005, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001654.
[184] I.Y. Wuni, Z. Wu, G.Q. Shen, J.T. Bugri, J. Frimpong-Asante, Benefit evaluation of design for excellence in industrialized construction projects, J. Architect. Eng. 27 (4) (2021) 505, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000505.
[185] S.A.S. Zakaria, Characterization of productivity aspects in building projects based on the adoption of Industrialized Building System (IBS), Malays. Constr. Res. J. 11 (3 Special Issue) (2020) 34–51.
[186] T. Duncheva, F.F. Bradley, Multifaceted productivity comparison of off-site timber manufacturing strategies in mainland Europe and the United Kingdom, J. Construct. Eng. Manag. 145 (8) (2019), 4019043, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001641.
[187] D.D. Viana, I.D. Tommelein, C.T. Formoso, Using modularity to reduce complexity of industrialized building systems for mass customization, Energies 10 (10) (2017) 1622, https://doi.org/10.3390/en10101622.
[188] I. Isaac, T. Bock, Y. Stoliar, A methodology for the optimal modularization of building design, Autom. ConStruct. 65 (2016) 116–124, https://doi.org/10.1016/j.autcon.2015.12.017.
[189] O. Moselhi, Z. Khan, Analysis of labour productivity of formwork operations in building construction, Construct. Innovat. 10 (3) (2010) 286–303, https://doi.org/10.1108/14714171011060088.

[190] M.-W. Park, N. Elsafty, Z. Zhu, Hardhat-wearing detection for enhancing on-site safety of construction workers, J. Construct. Eng. Manag. 141 (9) (2015), 4015024, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000974.

[191] E.A. Poirier, S. Staub-French, D. Forgues, Measuring the impact of BIM on labor productivity in a small specialty contracting enterprise through action-research, Autom. ConStruct. 58 (2015) 74–84, https://doi.org/10.1016/j.autcon.2015.07.002.

[192] A.S. Oyegoke, J. Kiiras, Development and application of the specialist task organization procurement approach, J. Manag. Eng. 25 (3) (2009) 131–142, https://doi.org/10.1061/(ASCE)0742-597X(2009)25:3(131).

[193] M. Hasan, M. Lu, Error propagation model for analyzing project labor cost budget risks in industrial construction, J. Construct. Eng. Manag. 147 (4) (2021), https://doi.org/10.1061/(ASCE)CO.1943-7862.0002010, 2010.

[194] P.-Y. Hsu, M. Aurisicchio, P. Angeloudis, Risk-averse supply chain for modular construction projects, Autom. ConStruct. 106 (2019), 102898, https://doi.org/10.1016/j.autcon.2019.102898.

[195] L. Kong, H. Li, H. Luo, Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction, J. Clean. Prod. 193 (2018) 684–701, https://doi.org/10.1016/j.jclepro.2018.05.037.

[196] A. Kanoglu, An integrated system for duration estimation in design/build projects and organizations, Eng. Construct. Architect. Manag. 10 (4) (2003) 272–282, https://doi.org/10.1108/09699980310489988.

[197] N. Dawood, E. Sriprasert, Construction scheduling using multi-constraint and genetic algorithms approach, Construct. Manag. Econ. 24 (1) (2006) 19–30, https://doi.org/10.1080/01446190500310486.

[198] P. Pons, M. Latapy, Computing communities in large networks using random walks, in: P. Yolum, T. Güngör, F. Gürgen, C. Özturan (Eds.), Computer and Information Sciences - ISCIS 2005. ISCIS 2005, Lecture Notes in Computer Science, vol. 3733, Springer, Berlin, Heidelberg, 2005, https://doi.org/10.1007/11569596_31.