Modular Construction in the Digital Age: A Systematic Review on Smart and Sustainable Innovations

Landing Page

Intended use
This Generalized Systematic Review Registration Form is intended as a general-purpose registration form. The form is designed to be applicable to reviews across disciplines (i.e., psychology, economics, law, physics, or any other field) and across review types (i.e., scoping review, review of qualitative studies, meta-analysis, or any other type of review). That means that the reviewed records may include research reports as well as archive documents, case law, books, poems, etc. This form, therefore, is a fall-back for more specialized forms and can be used if no specialized form or registration platform is available.

Citation
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Review Methods

In this section, you register the general type, background and goals of your review.

Type of review

Systematic Review

Review stages

Search, Screening, Extraction, Synthesis, Writing

Current review stage

Completed

Start date

20 September 2023

End date

06 December 2024

Background

1. Introduction
1.1. Background
The first prefabricated building prototypes date back to the Stone Age (specifically c. 400 000 B.C., during the Palaeolithic Period), when the nomadic people used raw materials such as trunks, branches, leaves, and animal furs and skins to build their temporary housing. In order not to be constantly searching for or working on these materials when moving to a different location, the nomads developed ways to assemble and disassemble their dwellings, using lightweight materials that they could carry with them (Staib et al., 2008).
In the Modern Age, with the expansion of the British Empire, prefabrication was introduced to the global market. As colonials, the British needed to build new houses fast. However, as they were unfamiliar with the raw materials in those newly found locations, they prefabricated building components in England so they could be sent to the colonies by maritime routes (Smith, 2009). Apart from the Anglophone countries, Scandinavia and Japan also have a long history of prefabricated construction, especially with wood (O'Brien, 2015; Savvides et al., 2023; Smith, 2009; Staib et al., 2008).
In the 20th Century, with the advent of mass production, there was a goal of creating an industrialized mass production system for buildings too, capable of optimizing efficiency and cost. Indeed, with the industrialization of the construction industry to build emergency shelters for both the military and civil population due to wars and economic crises, there were some innovative ideas to reach that goal (Carbone, 2019), although criticized for the lack of individuality of the construction (Khalili-Araghi and Kolarevic, 2020; Savvides et al., 2023). From this cooperation between architecture and the military industry, the first examples of prefabricated modular construction were materialized (e.g., the "Dymaxion House", the "Wichita House" and the "Standard of Living Package") (Carbone, 2019; Savvides et al., 2023; Staib et al., 2008). Even though these examples did not have connections with other identical modules, with the advance of this method, larger modular construction projects emerged by connecting multiple modules to form a single building. The recently deconstructed "Nakagin Capsule Tower" (Tokyo, Japan) was one of the earliest examples of a construction totally built through modules fully assembled off-site, which were then connected on the construction site (Staib et al., 2008). Before being deconstructed in 2022, this building was surveyed using reality capture techniques (drone and close-range photogrammetry, in addition to laser scanning) to preserve its cultural heritage digitally (gluon inc., 2022).
Indeed, new technologies are reshaping the construction industry, further extending its horizon towards the concept of Construction 4.0, where industrial production (e.g., prefabrication, modularization, 3D printing), cyber-physical systems (e.g., Internet of Things (IoT), sensors, drones) and digital technologies (e.g., Building Information Modelling (BIM), extended reality (XR), artificial intelligence, blockchain) enhance the productivity and efficiency of a sector known for its traditional methods and slow adoption of technological advancements and innovations (Brozovsky et al., 2024).
Per se, modular construction, allied to the concept of Design for Manufacture and Assembly (DfMA), provides numerous benefits compared to traditional alternatives: construction time is significantly reduced, and it is more predictable; lower construction costs; worker safety improvements due to operating on a safe and protected environment; improved quality; fewer workers on site; module manufacturing is no longer affected by external conditions (such as the weather or site accessibility), as it is done off-site; improvement of the project's sustainability by using more ecological and environmentally friendly

methods, as well as less waste of resources (Delgado et al., 2023; Gallo et al., 2021; Lee and Kim, 2017; Lu et al., 2021; Qi and Costin, 2023; Savvides et al., 2023).
Many countries have already implemented modular construction projects in their workflows, particularly the USA, the United Kingdom, Singapore, Australia, China and Hong Kong (Abdelmageed and Zayed, 2020; Alhawamdeh and Lee, 2024; Ikudayisi et al., 2023; Nguyen et al., 2022; Soltani et al., 2025; Wuni and Shen, 2020a, 2020b). Indeed, multiple studies have analysed the benefits and the barriers of implementing modular construction in the different continents (Alhawamdeh and Lee, 2024; Bello et al., 2024; Saliu et al., 2024; Soltani et al., 2025; Wuni et al., 2020; Wuni and Shen, 2020b). In this context, Ribeiro et al. (Ribeiro et al., 2022) studied the barriers to adopt modular construction in Portugal. The authors identified key issues such as lack of awareness of its benefits, the industry's resistance to innovate, difficulty in defining suitable projects, lack of certification organizations for components, and insufficient R&D levels in the industry. As such, the authors recommend setting policies such as professional training, certification of modular components, and integrating modular construction in engineering curricula. However, they emphasize the importance of increasing the industry's R&D efforts, developing value-based evaluation methods to compare the methodology to traditional approaches, and notably, promoting the use of digital tools.
In fact, by interconnecting modular construction with digital technologies, it is possible to extend its benefits, for instance, easier time scheduling and cost estimation, clash detection, improvement of stakeholder collaboration, parametric design optimization, and implementation of lean construction (Cheng et al., 2023; Darko et al., 2020; Yevu et al., 2023). These digital approaches are particularly important for this type of construction, as modularity demands cautious and detailed computerized design processes. Thus, by using these technologies, it is possible to avoid early-stage mistakes that can compromise module manufacturing. Moreover, these are also beneficial for the concept of module customization requirements from different customers (He et al., 2021).
From an environmental perspective, buildings account for 40% of energy consumed in the European Union, as well as 36% of energy-related direct and indirect greenhouse gas emissions. Therefore, in order to reach its goal of becoming climate-neutral by 2050, significant changes have to be made (Council of the European Union, 2023; The European Commission - Directorate-General for Climate Action, 2019; The European Commission, n.d.; The European Parliament and the Council of the European Union, 2024). As for buildings, sustainable and renewable energy allied to digitalization and smart buildings are crucial elements for transitioning into climate-friendly housing (The European Commission - Directorate-General for Climate Action, 2019).
The research project "R2UTechnologies – Modular System" addresses these topics, aiming to develop a disruptive concept of customizable modular construction centred in Portugal that can serve the global market, keeping in mind the current challenges of the construction sector regarding sustainability and environmental protection, in addition to its digital revolution (particularly focused on BIM and Digital Twins) (Recuperar Portugal: PRR - Plano de Recuperação e Resiliência, 2022).

1.2. Research Significance
Studies suggest that BIM is the most commonly used digital technology in off-site construction methodologies (Abanda et al., 2017; Abdelmageed and Zayed, 2020; Cheng et al., 2023; Olawumi et al., 2022). Data integration is currently a popular research area, including real-time monitoring connection between the physical and digital worlds, on what is known as a Digital Twin (Cheng et al., 2023). Rangasamy and Yang (Rangasamy and Yang, 2024) noted the importance of implementing BIM, IoT and artificial intelligence (AI) in the prefabrication design domain, particularly for quality and productivity enhancement. Khan et al. (Khan et al., 2023) identified critical risk factors for modular construction projects, while developing a risk mitigation framework for digital-based circular strategies in multiple life cycle stages, predominantly through the use of BIM, IoT, virtual/augmented reality (VR/AR) and AI. Moreover, the authors noted the potential of including digital fabrication and robotics in the module production process, which has been further explored by Fu et al. (Fu et al., 2024), highlighting how human-robot collaboration could enhance sustainability and safety in the modular construction production process.
In their literature review, Abanda et al. (Abanda et al., 2017) analysed multiple parameters in which BIM could enhance the benefits of off-site construction, in which sustainability is evaluated on its three pillars: Environmental, Social and Economic. The authors suggested that BIM could improve collaboration and communication between project partners, leading to an early anticipation of problems and reducing waste through improved construction management, thus, reducing project costs. Kamali and Hewage (Kamali and Hewage, 2016) reviewed the life cycle performance of modular buildings, providing insights into their environmental dimension, while identifying a research gap in evaluating the economic and social counterparts. In a more recent study, Nguyen et al. (Nguyen et al., 2022), noted that social sustainability remains the least focused dimension, suggesting it as a potential research topic for modular construction studies. However, these are out of scope of our study, which focus on the environmental contributions.
Abdelmageed and Zayed (Abdelmageed and Zayed, 2020) analysed the published literature on modular construction, identifying research trends in building design and construction management. Moreover, the authors emphasize the importance of assessing the sustainability of these projects, noting, for instance, that BIM-based parametric design allows the optimization of architectural options towards sustainable design, by evaluating the performance of each design proposal through sustainability simulation tools. In addition, the primary goal for a sustainable modular building must be on low energy consumption during the operation phase, thus, pursuing energy efficient targets such as the nZEBs (nearly-Zero Energy Buildings) and by adopting renewable energy resources (Kamali and Hewage, 2016; Nguyen et al., 2022). Savvides et al. (Savvides et al., 2023, 2018) analysed the integration of environmental systems and strategies in environmentally-friendly and technologically-advanced off-grid prefabricated housing units from multiple design and construction perspectives. These include the units' passive and active systems, bioclimatic design, ecological options (e.g., green roofs and recycled materials), construction materials and methods, as well as structural systems. However, their study did not address digital applications. In contrast, Yevu et al. (Yevu et al., 2023) reviewed the integration of digital technologies and prefabrication towards low-carbon efforts, focusing on energy evaluation, material selection, waste reduction, and process efficiency enhancements. Nonetheless, they did not explore climate-adapted passive or active building strategies, nor renewable energy sources. Nguyen et al. (Nguyen et al., 2022) also commented on how recent digital technological advancements have contributed to the sustainable development of modular construction, such as optimized designs and enhanced construction scheduling. Moreover, the authors acknowledged the role of IoT-based real-time monitoring for building performance data collection, noting that collaboration between academia and the industry would benefit these studies in the modular construction context, for example, to study the differences between the actual building performance and simulations.
As such, this publication is part of the early developments of a multidisciplinary collaborative project involving Portuguese industry and academia, thus, combining their expertise to push the boundaries of modular construction. For this purpose, the present literature review aims to cover recent modular construction advancements, so that it is possible to develop sustainable, efficient, intelligent, and high-performance modular construction systems that are customizable and scalable to meet diverse functional requirements (Recuperar Portugal: PRR - Plano de Recuperação e Resiliência, 2022). In fact, the literature suggests that there is a gap between industry and academia in the adoption of emerging technologies, including digital technologies and modular construction (Brozovsky et al., 2024). Therefore, collaboration between these two is essential to capacitate both ecosystems, not only for enhancing current practices but also for ensuring effective future training and capacity building (Brozovsky et al., 2024; Darko et al., 2020). This study will analyse digital-oriented modular construction solutions towards a sustainable and climate-neutral built environment, which has been identified by Ikudayisi et al., 2023 as a research gap. In particular, this review will extend towards circular economy and bioclimatic efforts, while also addressing the use of renewable energy sources and efficient energy design.

Primary research question(s)

This review examines the integration of digital technologies with modular construction methods, extending the analysis to circular and bioclimatic efforts, renewable energy sources, and passive building design strategies.

Secondary research question(s)

Assess recent advancements in digital-oriented modular construction towards a sustainable and climate-neutral built environment, identifying research trends and gaps based on three pillars: digital tools, building solutions, and environmental sustainability.

Expectations / hypotheses

Significant recent advancements are expected in the integration of digital technologies, such as BIM, IoT, and AI, within modular construction practices. These technologies are anticipated to enhance the efficiency, customization, and sustainability of modular construction projects.
Moreover, modular construction combined with digital technologies is expected to play a pivotal role in helping the European Union achieve its goal of climate neutrality by 2050. Innovative digital-oriented modular construction solutions are anticipated, supporting a sustainable and climate-neutral built environment.

Dependent variable(s) / outcome(s) / main variables

Main: Digital Applications, Building Solutions, and Environmental Sustainability
Secondary: Geography (Country and Continent), Year of Publication, Building Use, and Project Phase

Independent variable(s) / intervention(s) / treatment(s)

N/A

Additional variable(s) / covariate(s)

N/A

Software

Mendeley (version 1.19.4) and Rayyan (online platform)

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Conflicts of interest

The authors declare no conflicts of interest.

Overlapping authorships

We acknowledge that one of the studies included in this literature review has been authored by most members of the research team, titled "BIM and BEM Interoperability–Evaluation of a Case Study in Modular Wooden Housing" (Delgado et al., 2023). However, as the title suggests, this article is highly pertinent to the topic under analysis in this review. Therefore, we do not consider it a conflict of interest, given its relevance for the analysis. We firmly believe that our involvement as authors of a relevant study does not compromise the integrity or objectivity of the review.

Search Strategy

In this section, you register your search strategy: the procedures you designed to obtain all (potentially) relevant sources to review (e.g., articles, books, preprints, reports, case law, policy papers, archived documents).

Databases

Scopus and Web of Science

Interfaces

Scopus and Web of Science Core Collection

Grey literature

Out of scope

Inclusion and exclusion criteria

The PRISMA 2020 framework was employed to ensure the transparency and reproducibility of the study

The inclusion criteria are as follows:
• Articles focusing on "volumetric assemblies" (e.g., kitchens and bathrooms) and "modular buildings", according to Gibb's prefabrication taxonomy
• Articles that implement digital tools (notably BIM and Digital Twins) in modular construction case studies
• Year of publication: 2014 – 2023
• Document type: Articles
• Source type: Peer-reviewed Journals
• Language: English

The exclusion criteria are as follows:
• Articles not related to modular construction
• Articles that did not use BIM or Digital Twin-related applications
• Articles that are framework-only, thus, without case studies
• Unrelated to civil engineering or architecture

• Surveys and questionnaires
• Studies involving constructions other than buildings (e.g., bridges and tunnels)
• Non-residential buildings (e.g., hospitals, museums, classrooms)

Query strings

Example for combination: A AND B AND E

Scopus: TITLE-ABS-KEY ((modular OR prefabricated) AND (bim OR "Digital Twin" OR "Construction 4.0") AND (nzeb OR off-grid OR hous* OR passive OR smart)) AND (LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))

Web of Science: (Modular OR Prefabricated) AND (BIM OR "Digital Twin" OR "Construction 4.0") AND (nZEB OR Off-grid OR Hous* OR Passive OR Smart) (Topic) and Article (Document Types) and 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 (Publication Years) and Article (Document Types)

Search validation procedure

The effectiveness of the search strategy was ensured by testing the keywords and keyword groups. Adjustments were made based on these to confirm that the search strategy would capture relevant articles, thus validating the search procedure.

Other search strategies

N/A

Procedures to contact authors

No authors were contacted.

Results of contacting authors

N/A

Search expiration and repetition

The research strategy included a planned repetition, specifically, a a follow-up search was conducted in 2024 to capture articles published at the end of 2023 that were not collected in the initial search conducted in October 2023.

Search strategy justification

Scopus and Web of Science were the selected databases, partially due to being two of the largest multidisciplinary databases of peer-reviewed literature, thus, providing reputable sources of information, while being relevant for the research. Grey literature was not included in this review to ensure that only peer-reviewed publications were considered for analysis.
The keyword groups and combinations were carefully constructed to cover essential aspects of modular construction integrated with modern-day digital technologies towards a smart and sustainable built environment. These keyword groups and combinations were tested and adjusted accordingly to ensure they covered relevant literature to the topic.
No authors were contacted for this research, given that our analysis focused on the available publications only. Although some information was not retrieved from the articles, we opted to rely solely on the provided information.
An additional search was conducted in 2024 to collect articles published at the end of 2023 that were not included in the initial search performed in October 2023. Given that this review is part of an ongoing research project, to meet the established timeframe and objectives, new publications from 2024 could not be included. Therefore, the review only covers articles published up to the end of 2023.

Miscellaneous search strategy details

N/A

Screening

In this section, you register your screening procedure: the procedure you designed to eliminate all irrelevant sources from the results of the search strategy (and retain the relevant sources).

Screening stages

The screening process for this literature review was conducted in three stages, all by a single researcher. The first two stages were conducted simultaneously. Initially, the titles of all papers in the databases were reviewed (Stage 1). If there was any doubt about the relevance of a publication based on its title, the abstract and keywords were read (Stage 2). If there was still uncertainty regarding the relevance of a paper to the research, it was considered suitable at this stage to ensure proper assessment later.

In the final stage (Stage 3), the full texts of the articles were reviewed to confirm their eligibility. This thorough review process ensured that only the most relevant articles were included in the study.
Regarding the deduplication procedure, publications selected after the first two stages were placed in a reference manager software (Mendeley), which automatically removed most duplicates. Any remaining duplicates were then deleted manually by the researcher.

Screened fields / blinding

During the screening, all bibliographic fields, including titles, abstracts, authors, journal names, and publication years, were visible to the researcher. No fields were blinded, but the focus was primarily on the titles, abstracts, and keywords. Since the publication years were already within the range of 2014-2023, and attention was not particularly focused on other details, there was minimal risk of bias.

Used exclusion criteria

During the screening process, articles were excluded if they did not implement digital tools for prefabricated construction. As such, even though the research aimed to assess modular construction only, papers that used “prefabricated components or assemblies” and “non-volumetric prefabricated

assemblies" (according to Gibb's prefabrication taxonomy) were also initially included. This broader criterion was adopted to ensure no relevant article was mistakenly excluded.
To assess eligibility, all prefabrication studies were refined to cover exclusively modular construction methods, rather than prefabricated buildings in general. Articles that did not cover residential buildings and those that were framework-only were also excluded after full-text reading.

Screener instructions

No instructions were given to the screeners, as the screening process was conducted entirely by a single researcher, who also designed the criteria.

No files selected

Screening reliability

For this literature review, only one screener was used. As a result, there were no procedures implemented to ensure independent screening or to assess screener agreement. The single researcher conducted all stages of the screening process and designed the criteria used for inclusion and exclusion.

Screening reconciliation procedure

The screening process was conducted by a single screener; therefore, no reconciliation procedure was necessary.

Sampling and sample size

We identified 842 sources (925 including manually removed duplicates), from which 65 articles were considered relevant for the main analysis. All 925 references were categorized on Rayyan. While only 65 articles were used for the review itself, some of the excluded articles were used for complementary information. Based on these 65 publications, we were able to draw relevant conclusions for our analysis.

Screening procedure justification

During the screening rounds, we adopted a three-stage approach: title screening, abstract and keyword screening, and full-text screening. The first stage ensured that obviously irrelevant studies were immediately excluded, while abstract and keyword screening provided a more detailed overview. Finally, the full-text screening assessed the eligibility of the studies.
The inclusion and exclusion criteria were designed to ensure that the selected studies focused on digital-oriented modular construction applications. During the first two stages, to avoid mistakenly excluding relevant literature, we opted to include prefabricated construction in general for the analysis, which was then refined to modular construction only during the third stage of screening. The literature review aimed to cover recent case studies, thus the decision to cover articles published within the last 10 years at the time of the beginning of the research. In addition, framework papers were also excluded due to the lack of practical implementation. Given that English is the "lingua franca" of the current scientific literature, this was the reason to only cover publications in this language.
The blinding process was deemed unnecessary as the only data addressed at the initial stages consisted of titles, abstracts, and keywords. Since the screening process was conducted by a single researcher, there were no procedures for independent screening or reconciliation of divergent decisions. The researcher consistently applied the criteria across all stages of the screening process while maintaining rigour and objectivity.

Data management and sharing

We plan to make the sources and screening decisions from our database searches accessible. All relevant sources and screening decisions are compiled into a BibTeX file. This file will be available on the OSF (Open Science Framework) project repository. There are no embargos or restrictions on accessing the BibTeX file, and it will be freely accessible to anyone interested in reviewing the sources and screening decisions.

Miscellaneous screening details

N/A

Extraction

In this section, you register your plans for data extraction: the procedures you designed to extract the data you are interested in from the included sources. Examples of such data are text fragments, effect sizes, study design characteristics, year of publication, characteristics of measurement instruments, final verdicts and associated penalties in a legal system, company turnovers, sample sizes, or prevalences.

Entities to extract

The data extraction focuses on capturing several key entities from each included source. These include geographical and chronological information, as well as building use and the project phase. Additionally, to cover the three main categories of the literature review, the following were evaluated: the digital technologies implemented for modular construction studies, building construction solutions (including passive and active strategies), and environmental sustainability indicators.

Extraction stages

In the primary data extraction stage, a single researcher analyzed all articles and extracted the necessary information. When the primary researcher had doubts or required validation of the extracted information, co-authors specializing in the different fields were consulted and read the articles themselves. They then validated or corrected the extracted information to ensure accuracy and reliability.

Extractor instructions

When in doubt, the main researcher requested assistance from other co-authors, who served as extractor validators. For the digital technologies section, input was requested to determine whether articles qualified as Digital Twins or fell into related categories like Digital Shadows or Calibration Twins. Additionally, expertise was needed to classify machine learning, AI, optimization algorithms, and automation design tools.
In the building solutions section, co-authors were consulted to validate and correct the information on thermal properties.
For the sustainability section, assistance was requested to categorize nZEB and off-grid buildings, in addition to verifying the energy consumption and global warming potential (GWP) values.

No files selected

Extractor masking

N/A

Extraction reliability

For this study, a single extractor conducted all data extraction at an initial stage. Independent extraction procedures were not implemented.
To ensure the reliability and accuracy of the extracted data, the main researcher requested assistance from co-authors who served as extractor validators. When the primary researcher had doubts or required validation of the extracted information, the co-authors reviewed and either validated or corrected the information.
No formal test was used to assess extractor agreement, as the extraction was performed by a single researcher with validation support from co-authors.

Extraction reconciliation procedure

In case of differing opinions, the main researcher and the co-authors who acted as validators discussed them to reach a consensus on the extracted information. This process did not follow a formal procedure.

Extraction procedure justification

Each entity chosen for extraction was selected based on its direct relevance to the research questions and objectives. Our goal was to capture all critical variables and data points for a comprehensive understanding of the topic. Specifically, we acquired data on geographical and chronological information, building use, project phases, digital applications, building solutions, and environmental sustainability.
To ensure the reliability of the extracted data, we employed a two-step process. The main researcher, who conducted the screening procedure, also analyzed the data due to their familiarity with the content. When there were doubts, co-authors, who are experts in different fields of the review, were asked to aid in the validation of the extracted information. Any discrepancies were discussed and resolved through consensus. This process did not follow a formal procedure but relied on collaborative discussion to ensure accuracy.

Data management and sharing

The main paper provides an in-depth analysis of digital applications, building solutions, and environmental sustainability, as these are the main focus of the review. It also presents summarized information on geographical and chronological data, as well as building use and project phases. Additional details on building solutions and environmental sustainability can be found in the Supplementary Materials.

Miscellaneous extraction details

N/A

Synthesis and Quality Assessment

In this section, you register the procedure for the review's synthesis: the procedure you designed to use the data that was extracted from each source to answer your research question(s). This often includes transforming the raw extracted data, verifying validity, applying predefined inference criteria, interpreting results, and presenting results. Additionally, you register procedures you designed to assess bias in individual sources and the synthesis itself.

Planned data transformations

Data was grouped together in multiple tables across the review, summarizing and facilitating the comparison between studies. Additionally, averages were calculated according to the climate zones for comparison purposes.

Missing data

Missing data has been an issue, particularly when analyzing the passive building solutions. As mentioned in the Search Strategy, although some information could not be retrieved from the articles, we opted to rely solely on the available data. Therefore, we have acknowledged the limitations that this might introduce to our findings.

Data validation

As mentioned in the Data Extraction phase, a single researcher analyzed all articles, extracting and organizing all the necessary information. When in doubt, co-authors specialized in different fields were consulted and read the articles themselves. They then validated or corrected the information, ensuring accuracy and reliability.
For the digital technologies section, input was requested to determine whether articles qualified as Digital Twins or fell into related categories such as Digital Shadows or Calibration Twins. Additionally, expertise was needed to classify machine learning, AI, optimization algorithms, and automation design tools. In the building solutions section, co-authors were consulted to validate and correct the information on thermal properties. For the sustainability section, assistance was requested to categorize nZEB and off-grid buildings, in addition to verifying the energy consumption and global warming potential (GWP) values.

Quality assessment

N/A

Synthesis plan

Our research follows a mixed-method approach, incorporating both qualitative and quantitative information to investigate the tendencies in smart and sustainable modular construction. The qualitative data were collected and systematically arranged, identifying key themes and patterns. This information is primarily presented in tables, providing a structured and easily comprehensible overview.
For a thorough analysis, data are acquired for geographical and chronological analysis, as well as to assess the building uses and project phases. Particular attention is given to the main aspects of the review: digital technologies, building solutions, and environmental sustainability.

Criteria for conclusions / inference criteria

Conclusions are drawn based on the consistency and alignment of the information across multiple studies, rather than relying on pre-specified criteria.

Synthesist blinding

N/A

Synthesis reliability

This review was conducted by a single synthesist, with occasional consultation and validation from co-authors specialized in different fields. Throughout the analysis, when in doubt, co-authors reviewed the articles and provided input to ensure accuracy and reliability. This collaborative approach helped to validate and correct information across various sections, particularly related to the topics of digital technologies, building solutions, and environmental sustainability.

Synthesis reconciliation procedure

In the event of differing opinions, the main researcher and the co-authors who acted as validators discussed them to reach a consensus on the synthesized information. This process did not follow a formal procedure, relying on collaborative discussions to resolve discrepancies and ensure the accuracy of the synthesized data.

Publication bias analyses

Some articles in this review used the term "Digital Twin" loosely. Upon closer analysis, it was found that most of these articles did not fully implement this digital strategy. This potential bias was noted during the data extraction and synthesis phases.

Sensitivity analyses / robustness checks

No sensitivity analyses or robustness checks were conducted in this review.

Synthesis procedure justification

Our research followed a mixed-method approach, incorporating both qualitative and quantitative information to investigate tendencies in smart and sustainable modular construction. Qualitative data were grouped in multiple tables across the review, summarizing and facilitating comparisons between studies. Additionally, averages were calculated according to climate zones for comparison purposes. Particular attention was given to digital technologies, building solutions, and environmental sustainability. Moreover, for better characterization, data was acquired in terms of geography, year of publication, building uses, and project phases. In case of missing information in the articles, we decided to rely solely on what was available from the publications, acknowledging these limitations when applicable. Conclusions were drawn based on the consistency and alignment of information across multiple studies, rather than relying on pre-specified criteria, as it was what we found to be more aligned with our context.
The review process was conducted by a single researcher, who also performed the screening and extraction due to their familiarity with the topic. Occasional consultation and validation were requested from co-authors specializing in different fields. When in doubt, co-authors reviewed the articles and provided input to ensure accuracy and reliability. This collaborative approach helped validate and correct information across various sections, particularly related to digital technologies, building solutions, and environmental sustainability. In the event of differing opinions, the main researcher and co-authors discussed them to reach a consensus on the information. This process did not follow a formal procedure but relied on collaborative discussion to ensure accuracy.
It was expected that some articles would use the term "Digital Twin" loosely, as we covered in the review. Therefore, it was necessary to investigate this potential bias while reading the publications.

Synthesis data management and sharing

The main paper provides an in-depth analysis of digital applications, building solutions, and environmental sustainability, as these are the main focus of the review. It also presents summarized information on geographical and chronological data, as well as building use and project phases. Additional details on building solutions and environmental sustainability can be found in the Supplementary Materials.

Miscellaneous synthesis details

Senior researchers validated and corrected the written text, ensuring the accuracy and reliability of the synthesized information. This additional step helped to maintain the quality and integrity of the review process.