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Review

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

Diogo F. R. Parracho [1,*], Mohamed Nour El-Din [1], Iraj Esmaeili [1], Sara S. Freitas [2], Leonardo Rodrigues [2,3,4], João Poças Martins [1], Helena Corvacho [2], João M. P. Q. Delgado [2] and Ana Sofia Guimarães [2]

1 CONSTRUCT-GEQUALTEC, Department of Civil and Georesources Engineering, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; up201911753@up.pt (M.N.E.-D.); up202212109@up.pt (I.E.); jppm@fe.up.pt (J.P.M.)
2 CONSTRUCT-LFC, Department of Civil and Georesources Engineering, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; sarafreitas@fe.up.pt (S.S.F.); lrodrigues@fe.up.pt (L.R.); corvacho@fe.up.pt (H.C.); jdelgado@fe.up.pt (J.M.P.Q.D.); anasofia@fe.up.pt (A.S.G.)
3 ALiCE—Associate Laboratory for Innovation in Chemical Engineering, Department of Chemical and Biological Engineering, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
4 LEPABE—Laboratory for Process Engineering, Environment, Biotechnology and Energy, Department of Chemical and Biological Engineering, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
* Correspondence: dfrparracho@fe.up.pt

Abstract: Modular construction provides numerous benefits over traditional methods, especially when combined with digital technologies, offering a faster, safer, leaner, and more sustainable construction environment. This literature review follows the PRISMA method to 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. 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. While most articles focus on BIM uses, there is an increasing emphasis on IoT applications that leverage real-time data to achieve sustainability goals. However, no full-scale automated Digital Twin was found in this context. Additionally, Building Energy Modelling (BEM) and Life Cycle Assessment (LCA) tools are frequently discussed, reflecting the push for climate-friendly housing. Despite the interest in parametric and generative design, the integration of machine learning and artificial intelligence applications for sustainable modular construction strategies remains underexplored. Only a few papers acknowledged reaching nZEB requirements despite the great emphasis on passive building solutions and renewable energy sources that contribute to this goal. However, material circularity has yet to achieve its full potential for sustainable modular construction. Moreover, there is some interest in off-grid modular buildings, although further research should be undertaken to analyse the modular construction feasibility for sustainable off-grid communities. Furthermore, the findings highlight the potential of digitalisation in modular construction to enhance efficiency and ensure environmental sustainability within the Architecture, Engineering, and Construction (AEC) sector.

Keywords: modular construction; construction 4.0; design for manufacture and assembly (DfMA); circular construction; environmental sustainability

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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 [1].

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 [2]. Apart from the Anglophone countries, Scandinavia and Japan also have a long history of prefabricated construction, especially with wood [1–4].

In the 20th century, with the advent of mass production, there was a goal of creating an industrialised mass production system for buildings that was capable of optimising efficiency and cost. Indeed, with the industrialisation 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 [5], although criticised for the lack of individuality of the construction [4,6]. From this cooperation between architecture and the military industry, the first examples of prefabricated modular construction were materialised (e.g., the "Dymaxion House", the "Wichita House" and the "Standard of Living Package") [1,4,5]. 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 and were then connected on the construction site [1]. 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 [7].

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, modularisation, 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 [8].

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 performed off-site; improvement of the project's sustainability by using more ecological and environmentally friendly methods, as well as less waste of resources [4,9–13].

Many countries have already implemented modular construction projects in their workflows, particularly the USA, the United Kingdom, Singapore, Australia, China and Hong Kong [14–20]. Indeed, multiple studies have analysed the benefits and the barriers of implementing modular construction in different continents [16,17,20–23]. In this context, Ribeiro et al. [24] studied the barriers to adopting modular construction in Portugal. The authors identified key issues such as a lack of awareness of its benefits, the industry's resistance to innovate, difficulty in defining suitable projects, lack of certification organisations 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 into engineering curricula. However, they emphasise 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 optimisation, and implementation of lean construction [25–27]. These digital approaches are particularly important for this type of construction, as modularity demands cautious and detailed computerised 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 customisation requirements from different customers [28].

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 [29–32]. As for buildings, sustainable and renewable energy allied to digitalisation and smart buildings are crucial elements for transitioning into climate-friendly housing [31].

The research project "R2UTechnologies—Modular System" addresses these topics, aiming to develop a disruptive concept of customisable 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) [33].

1.2. Research Significance

Studies suggest that BIM is the most commonly used digital technology in off-site construction methodologies [18,26,34,35]. 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 [26]. Rangasamy and Yang [36] 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. [37] 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. [38], highlighting how human–robot collaboration could enhance sustainability and safety in the modular construction production process.

In their literature review, Abanda et al. [34] 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 [39] 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. [19] 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 the scope of our study, which focuses on the environmental contributions.

Abdelmageed and Zayed [18] analysed the published literature on modular construction, identifying research trends in building design and construction management. Moreover, the authors emphasise the importance of assessing the sustainability of these projects, noting, for instance, that BIM-based parametric design allows the optimisation of architectural options toward 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 low energy consumption during the operation phase, thus pursuing energy-efficient targets such as the nZEBs (nearly-Zero Energy Buildings) and adopting renewable energy resources [19,39]. Savvides et al. [4,40] 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, and structural systems. However, their study did not address digital applications. In contrast, Yevu et al. [27] 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 or renewable energy sources. Nguyen et al. [19] also commented on how recent digital technological advancements have contributed to the sustainable development of modular construction, such as optimised 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 customisable and scalable to meet diverse functional requirements [33]. 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 [8]. 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 [8,25]. This study will analyse digital-oriented modular construction solutions for a sustainable and climate-neutral built environment, which has been identified by Ikudayisi et al. [14] 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.

The rest of this literature review is structured as follows: Section 2 elaborates on the adopted strategy to conduct the review itself; Section 3 provides the results and some analysis from multiple perspectives, starting with general information (such as geographical and chronological distribution), then building use and project phase, and finally the three main assessments of the review—digital implementation, building construction solutions including their respective passive and active systems, and the environmental perspective; Section 4 discusses the results, whereas conclusions are drawn in Section 5.

2. Methods

This section presents the methodology used to conduct the literature review of the current state of the art. This study followed the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) Statement [41], covering publications until the end of 2023. As such, a systematic literature review was conducted following Gibb's prefabrication taxonomy [42]. Hence, in this review, only articles that include "volumetric assemblies" (e.g., kitchens, bathrooms) and "modular buildings" are considered for the analysis.

This literature review started by acquiring articles from two of the largest multidisciplinary databases of peer-reviewed literature: Scopus and Web of Science. Five keyword groups were created to generate the search string combinations (Tables 1 and 2) used under the "Article Title, Abstract, Keywords" research field.

Table 1. Keyword groups.

Group A	Group B	Group C	Group D	Group E
Modular	BIM	DfMA	Sustainab*	nZEB
Prefabricated	"Digital Twin"	"Design for Manufacturing"	Lean	Off-grid
-	"Construction 4.0"	"Design for Assembly"	Energ*	Hous*
-	-	"Design for Disassembly"	Lifecycle OR "Life Cycle"	Passive
-	-	IPD OR "Integrated Project Delivery"	Circular [economy, construction]	Smart [systems, buildings, sensors]

Table 2. Keyword search combinations.

	Keyword Combinations
A AND B AND C	(Modular OR Prefabricated) AND (BIM OR "Digital Twin" OR "Construction 4.0") AND (DfMA OR "Design for Manufacturing" OR "Design for Assembly" OR "Design for Disassembly")
A AND B AND D	(Modular OR Prefabricated) AND (BIM OR "Digital Twin" OR "Construction 4.0") AND (Sustainab* OR Lean OR Energ* OR Lifecycle OR "Life Cycle" OR Circular)
A AND B AND E	(Modular OR Prefabricated) AND (BIM OR "Digital Twin" OR "Construction 4.0") AND (nZEB OR Off-grid OR Hous* OR Passive OR Smart)
A AND C AND D	(Modular OR Prefabricated) AND (DfMA OR "Design for Manufacturing" OR "Design for Assembly" OR "Design for Disassembly" OR IPD OR "Integrated Project Delivery") AND (Sustainab* OR Lean OR Energ* OR Lifecycle OR "Life Cycle" OR Circular)
A AND C AND E	(Modular OR Prefabricated) AND (DfMA OR "Design for Manufacturing" OR "Design for Assembly" OR "Design for Disassembly") AND (nZEB OR Off-grid OR Hous* OR Passive OR Smart)
A AND D AND E	(Modular OR Prefabricated) AND (Sustainab* OR Lean OR Energ* OR Lifecycle OR "Life Cycle" OR Circular) AND (nZEB OR Off-grid OR Hous* OR Passive OR Smart)

These groups reflect modular construction and prefabricated construction in general (Group A) to avoid missing any useful articles in this phase. The main digital tools that the research project will focus on are included in Group B, whereas the methodologies of modular projects are displayed in Group C. The other keyword groups represent sustainable and lean construction. This review intends to study modular construction integrated with modern-day digital technologies towards a smart and sustainable built environment; therefore, all keyword search combinations included Group A, which specifically addresses this kind of prefabricated construction. The first three combinations focus directly on the digital approach, while the remaining ones focus on sustainable construction, which may also have these digital methods, but indirectly.

In the first stage of data collection from the PRISMA workflow, 7622 articles were identified through database searching. Among these, 4944 were excluded as they did not meet the research criteria when refining the results with the following filters:

- Year of publication: 2014–2023;
- Document type: Articles;
- Source type: Peer-reviewed journals;
- Language: English.

The remaining 2678 articles were screened, with 1217 of them eventually excluded after reading the paper's title and abstract, as they did not meet the inclusion criteria (i.e., using digital tools for modular construction applications). If there was any uncertainty regarding the relevance of a paper to the research, it was considered suitable at this stage so that it could be properly assessed later. Therefore, during this initial process, a broad criterion was adopted so that no relevant articles were mistakenly excluded. 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 [42]) were also initially included.

Then, the 1461 papers that met these requirements were introduced into reference manager software (Mendeley v1.19.4). Automatically, the software removed 536 duplicates; however, not all the duplicates were immediately deleted, given that 83 had to be discarded manually. Note that this automatic removal process was the only instance not performed by a human. Thus, at the end of this stage, 842 articles remained, which were then read to assess their eligibility.

Eventually, when assessing the paper's eligibility, 777 were considered irrelevant for the literature review, as they did not meet the research requirements. In other words, to be eligible, a paper must implement digital tools—notably BIM and Digital Twins—in modular construction case studies. Hence, at this stage, all prefabrication studies were refined to cover exclusively modular construction methods rather than prefabricated buildings in general.

The reasons for paper exclusion at this stage are as follows: not being related to modular construction; not being related to either BIM or Digital Twins (or Digital Shadows); being framework only and, therefore, not having case studies; not being related to civil engineering or architecture; and being questionnaires or surveys. Other reasons for exclusion are related to the aimed applications the "R2U" project intends to reach (residential buildings, hotels, student and senior residences). Therefore, articles that included constructions other than buildings such as tunnels [43–45], bridges [46–49], and piping [50–52] were immediately excluded. Also, if the building uses were not in accordance with the residential criteria, these were also excluded, including greenhouses [53], hospitals [54] and infectious diseases treatment units [55], museums [56], industrial [57,58] and animal creation buildings [59,60], spas [61], classrooms [62], and even blockhouse bunkers [63].

At the end of the process, 65 articles remained to be fully assessed during the review. Figure 1 shows the PRISMA flowchart of this research:

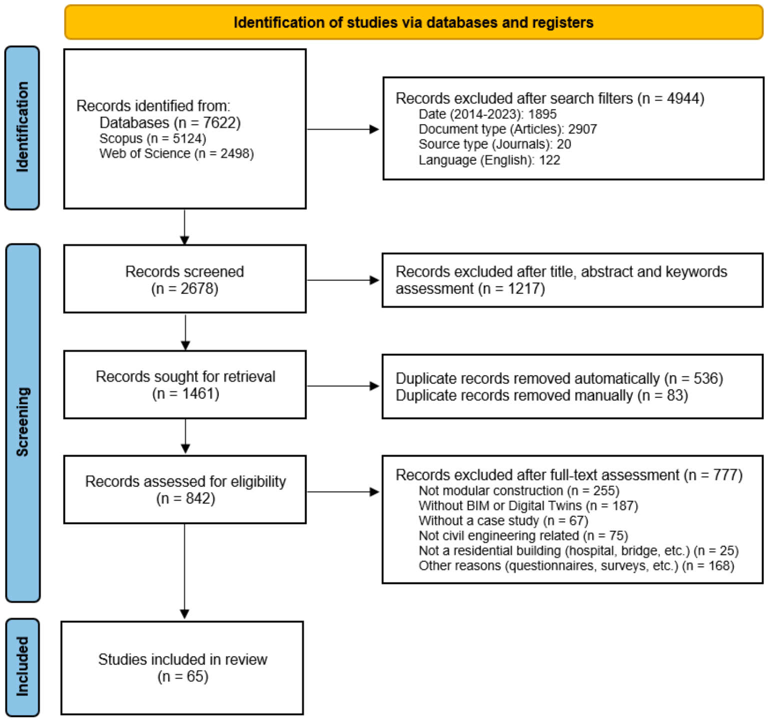

Figure 1. Literature review flowchart based on the PRISMA 2020 Statement [41].

3. Results

3.1. Geographical and Chronological Analysis

After finishing the article-gathering process based on the PRISMA Statement, the articles collected are assessed thoroughly at this stage. Firstly, general data are evaluated.

Regarding the distribution of each article case study location, it is possible to observe the major impact of Asian studies, followed by Europe and North America. The countries with the most case studies are Hong Kong SAR (14), Mainland China (11), and the USA (7). These data can be seen in Figure 2. Note that an article can report multiple case studies, so they are counted individually, which totals 76 distributed by 65 publications. For conceptual studies, it is important to count the case studies differently to prevent potential biases. For example, Najjar et al. [64] studied the implementation of a building in eight different locations within Brazil. Therefore, if each location was counted independently, it would falsely inflate Brazil's data and, thus, the ranking on the list. Therefore, conceptual case studies are counted once per country to maintain data accuracy for situations similar to this.

The geographical distribution of the case studies aligns with the existing literature on the connection between digital technologies and integrated practices in the AEC sector, including modular construction, with a particular focus on Asia, North America, and Europe [14]. As mentioned, Hong Kong has the most contributions to this review, which is expected given that it is one of the regions where modular construction practices are widely adopted, alongside Mainland China [14]. This high level of adoption can be partially explained by the limited space available for construction in densely populated urban areas, which makes modular construction methods particularly advantageous for high-rise buildings [65].

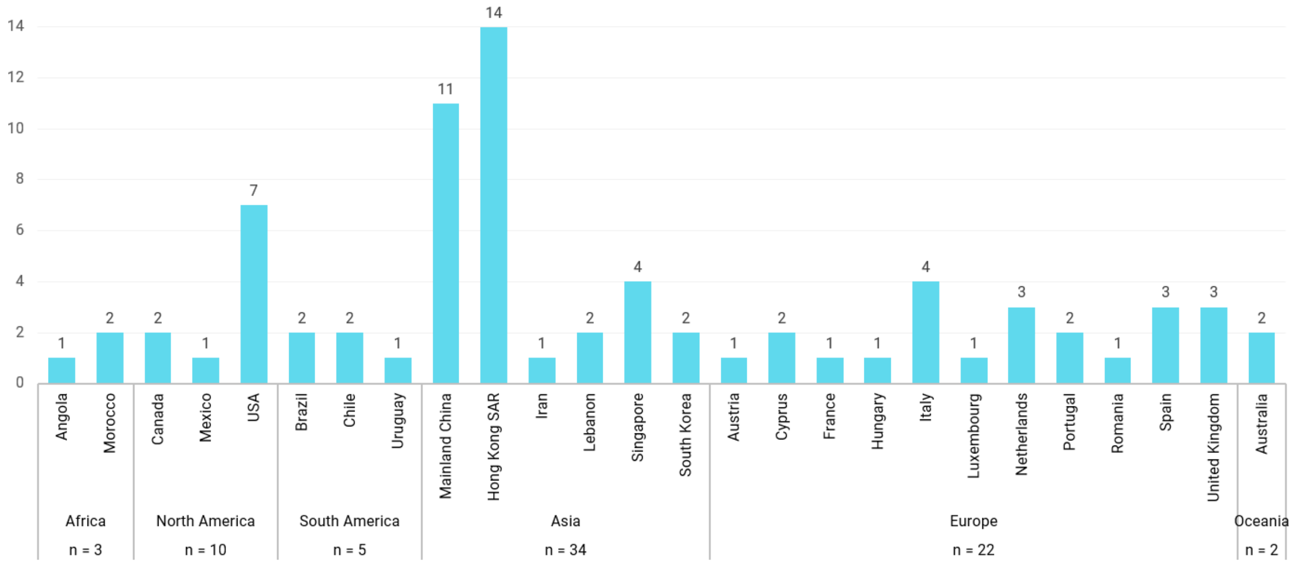

Figure 2. Case studies' geographical distribution.

Some studies have focused on identifying the drivers and barriers to implementing modular construction workflows. For instance, Wuni and Shen [15] identified 120 barriers, which they classified into eight clusters: knowledge, attitudinal, financial, technical, aesthetic, industry, process, and policy. Similarly, Alhawamdeh and Lee [17] categorised 47 barriers into six groups: political, economic, social, technical, legal, and environmental.

Political and legal barriers directly influence modular construction adoption by shaping policies, regulations, standards, and guidelines. Therefore, governmental support is considered a key factor in the implementation of modular construction in Asia, namely in China, Hong Kong, and Singapore [15–18,20,21,23]. Similar initiatives have been introduced by other non-Asian governments, such as Australia, the USA, and the United Kingdom [15,20,21]. However, the lack of supportive policies in some countries continues to favour traditional construction methods. As noted by Akinradewo et al. [65], if governments in developing countries do not develop policies and regulations to incentive the implementation of modular construction solutions, stakeholders may be reluctant to explore alternative construction methods. Some suggested incentives include tax discounts and faster approval processes [21]. As such, it is essential that governments collaborate with the industry to initiate these projects and establish incentives to encourage their adoption [21,65].

Implementing modular construction requires skilled labour and powerful lifting equipment. Despite these resources being easily available in developed countries, they pose significant challenges in developing countries [15,21,65]. In fact, specialised expertise is fundamental for the successful adoption of off-site construction methods [17,65], as without it, these solutions could result in a low market demand [65]. Skilled workers and specialised knowledge are essential for the effective implementation of modular construction, as they have a direct impact on the performance and quality of the projects [17]. Therefore, it is crucial to provide adequate training to improve both technical and managerial knowledge related to these methods [15,17,21]. While developed countries that regularly implement off-site construction methods tend to further explore its benefits, such as for sustainability purposes, emerging markets rather focus on foundational challenges, including specialised skills development [20].

Developed nations highlight that substantial capital investment and inadequate regulatory guidance can lead to financial losses in modular construction. Moreover, high project costs, limited economies of scale, and transportation expenses also contribute to these losses [17,20]. For instance, countries with limited capacity to manufacture and supply modules face expensive logistics due to cross-border transportation [15]. Moreover, in geographically vast countries like Australia, dispersed population centres make module transportation costly and negatively impact the supply chain efficiency due to extensive delivery times [20].

European case studies are prevalent in this literature review, although dispersed. Soltani et al. [20] noted that Europe emphasises sustainable practices and industry transformation, including off-site building construction, which aligns with the European sustainability goals [29–32]. In addition, the authors also acknowledged the contribution of North America, especially the USA, in this research field. According to Feldmann et al. [66], studies addressing the barriers to prefabricated construction in regions with a well-developed modular construction market, notably in Europe, are already outdated. Similarly, Ribeiro et al. [24] surveyed the Portuguese industry to assess the barriers to modular construction in the country as a representative of the European market, given the lack of updated information on the European Union construction market. The main barriers identified in Portugal include low levels of R&D, lack of accredited organisations to certify the manufactured components' quality, and the industry's resistance to innovation.

There is a lack of detailed scientific studies about the levels of modular construction adoption in South America [15,17,67], which, according to Medeiros and Melo [67], extends to the entire Latin America. This scarcity suggests a low level of priority given to off-site construction methods by both the industry and governments in the region [17,68], thus highlighting the conservatism within South America's AEC industry [68].

Interestingly, no publications were found covering island nations from the Caribbean or the Pacific that thoroughly followed all inclusion criteria despite some examples of prefabricated housing studies [69–71]. For instance, Shahzah et al. [72] analysed the barriers and enablers of modular construction implementation in New Zealand. Among their findings, the authors noted the lack of digital innovation in this field, particularly regarding BIM applications for this context.

Considering the interest in providing improved and suitable temporary housing for refugees in Africa and the Middle East [73], the authors were expecting to gather more publications on these regions. Apart from the issues already addressed regarding off-site construction adoption in developing countries, this limitation could also be attributed to the countries' level of BIM adoption, in addition to the barriers to integrating digital tools with modular construction, such as high software costs and skill shortage [22]. Furthermore, as mentioned in the Introduction, Scandinavian countries and Japan have a long history of prefabricated construction, particularly with wood [1–4]. However, no article from these regions was found that fully met all criteria concerning the implementation of digital solutions alongside modular construction for residential purposes.

No article was found addressing case studies located in Antarctica; nevertheless, prefabricated and modular construction are part of the continent's architectural history [74]. As noted by Noor et al. [75], containers are commonly used as transportable laboratories for Antarctic research; therefore, the authors developed a solution with the intend of minimising environmental impacts by adopting a green building philosophy. Other authors have developed sustainable modular building solutions [76–79]; however, none of these met our review's inclusion criteria. Despite the strict construction restrictions in Antarctica and considering the emphasises on environmental protection under the Antarctic Treaty [80], it could be interesting to explore how digital tools could enhance environmental sustainability within the Antarctic built environment.

From the article's data, it is also possible to analyse their chronological distribution per year. Figure 3 shows that in the initial years, the number of published articles was quite low, reflecting the early stages of digital integration with modular construction, with limited research and experimentation. However, during these years, the overall interest in modular construction was on the rise [18], with an emphasis on sustainability, driven by the introduction of the Sustainable Development Goals (SDGs) [19]. Then, there was a period of gradual increase, indicating a growing interest in the potential benefits of combining digital tools with this kind of off-site construction. According to Abdelmageed and Zayed [18], this is where modular construction research reached its peak before the onset of the COVID-19 pandemic.

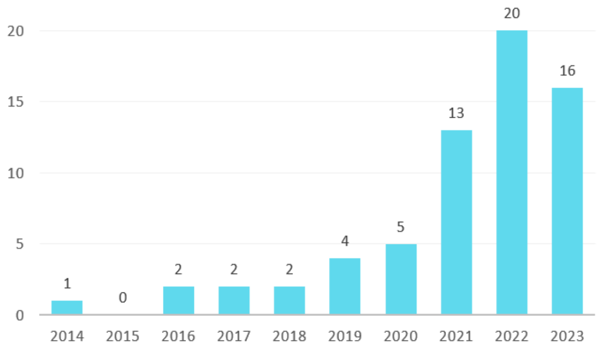

Figure 3. Article chronological distribution by year.

Afterward, there is a spike in the number of articles linking digital approaches with modular construction. The pandemic disrupted investments in new technologies within the sector [81], which impacted off-site construction in general [82]. For instance, during the COVID-19 outbreak, there was an urgent need to build hospitals quickly, thus leading to the adoption of modular construction workflows for these projects [54,83]. The research peak, however, occurs during the post-pandemic period, indicating a renewed focus on these approaches. It is also noteworthy that while the initial post-pandemic surge seems to have stabilised, the integration of digital tools in the context of modular construction remains a significant area of interest [19]. This trend is also associated with an increased awareness of environmental issues and the importance of addressing global climate change [19,20].

3.2. Building Use and Project Phase

To better understand the applications of modular construction from the collected papers, they were distributed by their building use and project phase, in addition to the continent where they are located. Table 3 shows the overview of all these data, while Tables 4 and 5 summarise them.

Table 3. Article distribution by continent, building use, and project phase.

Continent	Building Use	Project Phase				Number of Articles	References
		Design	Off-Site	On-Site	O&M		
Africa	Residential	X	-	-	-	2	[84,85]
North America	Residential	X	-	-	-	5	[86–90]
		-	X	-	-	1	[91]
		-	X	X	-	1	[92]
	Temporary Housing	X	-	-	-	1	[93]
	Senior Residence	-	X	-	X	1	[94]
	Hotel	X	-	-	-	1	[10]
South America	Residential	X	-	-	-	3	[64,85,95]
		-	-	-	X	1	[96]
	Prototype	X	-	-	-	1	[97]

Table 3. *Cont.*

Continent	Building Use	Project Phase				Number of Articles	References
		Design	Off-Site	On-Site	O&M		
Asia	Residential	X	-	-	-	5	[98–102]
	Multi-Storey Residential	X	-	-	-	6	[28,99,103–106]
		-	X	-	-	1	[11]
		-	X	X	-	5	[107–111]
		-	-	X	-	1	[112]
		-	-	-	X	2	[113,114]
	Temporary Housing	X	-	-	-	3	[115–117]
	Senior Residence	-	-	-	X	1	[118]
	Student Residence	X	-	-	X	1	[119]
	Multifunctional	-	X	X	-	1	[120]
	Bathroom (only)	X	-	-	-	1	[121]
		-	X	-	-	1	[122]
	Prototypes	X	-	-	X	1	[123]
		X	-	X	-	1	[124]
		-	-	-	X	2	[125,126]
Europe	Residential	X	-	-	-	4	[4,127–129]
		X	X	X	-	1	[130]
		X	-	-	X	1	[85]
		-	-	-	X	3	[9,131,132]
	Multi-Storey Residential	X	-	-	-	3	[128,129,133]
		-	-	-	X	1	[134]
	Temporary Housing	X	-	-	-	2	[135,136]
	Student Residence	X	-	-	-	1	[137]
	Prototypes	X	X	-	-	1	[138]
		-	-	X	X	1	[139]
		-	-	-	X	1	[140]
Oceania	Bathroom (only)	X	X	-	-	1	[141]
	Prototype	X	-	-	-	1	[142]

Table 4. Article distribution by building use.

Building Use	Number of Articles	References
Residential	25	[4,9,64,84–92,95,96,98–102,127–132]
Multi-Storey Residential	19	[11,28,99,103–114,128,129,133,134]
Temporary Housing	6	[93,115–117,135,136]
Senior Residence	2	[94,118]
Student Residence	2	[119,137]
Hotel	1	[10]
Multifunctional	1	[120]
Bathroom *	3	[121,122,141]
Prototype	9	[97,123–126,138–140,142]

NOTE (*): Modular bathroom pods are individually included too. If integrated into a building, these are included in the category of the building itself.

Table 5. Article distribution by project phase.

Project Phase	Number of Articles	References
Design	41	[4,10,28,64,84–90,93,95,97–106,115–117,119,121,123,124,127–130,133,135–138,141,142]
Off-Site Construction	14	[11,91,92,94,107–111,120,122,130,138,141]
On-Site Construction	11	[92,107–112,120,124,130,139]
O&M	15	[9,85,94,96,113,114,118,123,125,126,131,132,134,139,140]

O&M—Operations and Maintenance. NOTE: An article can be included in more than one project phase.

From the previous tables, it is possible to observe a clear tendency towards residential buildings (including high-rise and mid-rise buildings). Indeed, most reviewed papers are related to single or double-storey modular housing. North America and Europe are the continents where these buildings are more common in the literature, whereas Asian countries focus mainly on high-rise construction. Temporary housing is also tackled in some cases, especially due to humanitarian crises caused by wars or natural disasters [93,116,117,136].

Three papers were found to be only focused on bathroom pods [121,122,141]; nonetheless, these are not the only instances where these types of modules were used in other works. Indeed, nine other articles [11,92,96,100,101,103,108,113,134] also benefitted from using bathroom pods, in addition to three kitchen pods [101,103,113] and one laundry module [96]. It should be noted, however, that six of these additional bathroom pods were identified on non-modular prefabricated buildings: four related to high-rise construction [103,108,113,134] and two low-rise residential buildings [92,96]. Notwithstanding, following this review's article selection criteria, the fact that these publications implemented "volumetric assemblies" (according to Gibb's taxonomy [42]) enables the inclusion of these hybrid constructions into the analysis.

Some modular buildings found in the review have a specific demographic target: seniors and young students. For senior citizens, both Colistra [94] and Jin et al. [118] presented residential solutions with smart home devices for elder healthcare monitoring. Regarding younger people, particularly university students, both cases presented are multi-storey buildings: a 19-storey building in Hong Kong [119] and a 25-storey in Wolverhampton, United Kingdom [137]. In addition, one of the buildings presented by Oorschot and Asselbergs [129], namely the multi-storey solution (MOOS), is also mentioned that it can be for both young and old users.

Regarding the project phase assessed in the articles, most of them focused on the design stage. As previously mentioned, digital technologies improve modular construction's detailed design processes, aiming to reduce initial mistakes, improve collaborative tasks, and optimise designs [25–28]. In fact, collaborative BIM-based modular building design was the chosen process for the hotel case study [10]. It is also beneficial for clients' customisation demands [28,102]. Indeed, some articles' modules are customisable [4,9,84,97,98,101,102,127,129,131,135,138].

Only two articles were found regarding on-site construction alone: a study focused on optimising prefabricated construction using cranes [112] and a prototype that simulates on a small scale the Digital Twin of on-site operations and its respective digital counterpart [124]. Authors focus on either off-site construction only [11,91,122] or on the full construction phase, starting on the off-site prefabrication assembly, module transportation, and, then, on the on-site construction. In this case, except for the Canadian study of Salama et al. [92], all examples of this method are located in Hong Kong [107–111,120], with most of them addressing high-rise buildings [107–111], besides the MiC Resources Centre [120], which is a multifunctional space (including hotel, hostel, exhibition and residential areas) [143]. Moreover, Ezzeddine and García de Soto [130] focus on the process described before in addition to the design stage, managing and coordinating multiple teams through a digital platform.

The studies that focus on off-site construction alone are related to the assembly of residential modules, including an entire apartment and, also, on a bathroom pod. Lee and Kim [11] studied apartment module manufacturing productivity based on BIM, similar to Podder et al. [91], which integrated BIM-based lean methodologies in the module factory. Meanwhile, Tan et al. [122] focused on as-built geometric data collection with a laser scanner for further comparison with quality standards.

Besides this study by Tan et al. [122], there are two other instances in which a bathroom pod was the only case study of an article selected for this literature review: Sun and Kim [121] developed a method for automatic rule checking verification of BIM objects during the design stage, based on Singapore's guidelines, whereas Wasim and Oliveira [141] optimised the structural design based on DfMA in addition to the off-site construction process of bathroom pods based on BIM. It should be noted that Pérez-Valcárcel et al. [138] also focused on the design stage and the off-site construction phase, which, on this occasion, was related to temporary housing.

From the assessed papers, apart from the design stage, operations and maintenance (O&M) is the construction phase with the most publications, focusing on this post-construction stage, namely for retrofitting strategies, lifecycle assessments (LCA) of existing buildings, and the evaluation of the indoor thermal comfort. Vassiliades et al. [131] and Garcia et al. [96] studied existing buildings but from the retrofitting perspective. The former analysed an active solar system panel integration on an existing building, while the latter addressed improvement strategies for energy efficiency using data mining tools. In addition, Moga et al. [140] examined solutions to improve their Romanian prototype, aiming to reach the nZEB certification (i.e., a building with high energy performance, where the nearly zero or very low amount of energy needs are significantly covered by on-site or nearby renewable energy sources [32]). Meanwhile, Faraj et al. [125,126] conducted several experimental studies based on monitoring campaigns from an energy and thermal comfort standpoint of their prototypes, intending to optimise the use of phase change materials (PCM), given the Lebanese reality. Delgado et al. [9] opted for a distinct approach, creating an as-is BIM model based on aerial photogrammetry for thermal comfort assessment purposes, using monitoring campaigns as well. Moreover, Jin et al. [118], Colistra [94], and Pérez-Valcárcel et al. [138] also implemented monitoring devices in their studies, with the former adopting a "smart home" perspective, while the latter used temperature and humidity sensors. Meanwhile, Ansah et al. [113], Antwi-Afari et al. [114], and Arslan et al. [134], in addition to Kechidi and Banks [132], analysed the LCA of their respective buildings based on the BIM methodology.

Finally, two publications focused on both the design stage and O&M [85,123]. That means that these authors used real buildings in addition to a strong presence of simulations and design options. For example, for LCA and energy analysis, Tavares and Freire [85] studied an existing modular building in Aveiro, Portugal. In addition, simulations are conducted to assess the differences in case of being located in other climate zones (including Luanda, Rio de Janeiro, and Casablanca, among others). Unusually, because of these simulations, this paper appears more than once in Table 3. It should be noted that a similar logic is followed by Kristiansen et al. [123], although, in this case, applicable to the climate zones of China.

Previous modular construction literature reviews have concluded that while most studies focus on the construction phase—both off-site and on-site, in terms of construction management and operations, including scheduling, costing, risk assessment, and contract management [14]—there is also significant emphasis on the design stage [14,18]. As stated by Abdelmageed and Zayed [18], "the critical stage in modular construction is the design stage". It enables coordination and collaboration between stakeholders, clash detection, and lean construction [18,26,37], particularly when allied to BIM tools, facilitating the designing of material circularity and DfMA processes [37].

According to Ikudayisi et al. [14], most modular construction studies tend to focus on the construction phase itself; however, they often overlook the potential of digital technologies. For instance, despite BIM applications providing tools to integrate time, cost, facility management, and sustainability variables, most studies fail to incorporate these during the construction phase, instead focusing on the design process [14]. This aligns with our findings, where the design stage has been identified as the most explored phase towards smart and sustainable digital-oriented modular construction. Moreover, given the DfMA philosophy of modular construction, some articles have explored the potential of material circularity, notably through LCA studies; however, none implemented their methods on an actual deconstruction scenario. As such, future works could potentially explore this research gap.

3.3. Digital Technologies Applied to Modular Construction

Construction 4.0 is reshaping the construction industry based on new technologies, enhancing the productivity and efficiency of a sector known for its traditional methods and slow adoption of technological advancements and innovations [8]. Integrating modular construction and digital technologies can, therefore, extend its benefits for all the stakeholders in the construction industry [25–28]. The "R2UTechnologies" research project is particularly interested in two of these digital practices: BIM and Digital Twins.

According to ISO 19650 [144], Building Information Modelling (BIM) can be defined as "a shared representation of a built asset to facilitate design, construction and operation process to form a reliable basis for decisions". BIM has become an indispensable tool for the construction industry, enabling the virtual reconstruction of construction assets at any phase of its lifecycle. As such, this technology has played a crucial role in the digital transformation of the sector. Moreover, BIM models are also often used as the digital basis to create a Digital Twin [145].

In the absence of standard specifications, there are multiple definitions of a Digital Twin [146]. As this term is broadly used, it is regularly confused with Digital Shadow and even BIM [147]. Real-time data devices must be installed on real assets to create a Digital Twin, enabling a bidirectional connection between the physical and digital worlds while triggering automated actions through alert systems or actuators. Therefore, the data move from the physical asset to the digital world and vice versa. However, in a Digital Shadow, these data flow unidirectionally, and the virtual model cannot influence the physical asset directly, thus requiring manual actions [147–149].

Apart from these definitions, another term will be used during this review. When using real sensors whose in situ monitoring data are used for calibration purposes and, often, compared to simulation results (e.g., temperatures), the term "Calibration Twin" will be used. Figure 4 illustrates these terminologies.

Although BIM is the most dominant digital technology in the construction industry, others are emerging, such as the IoT (which correlates with Digital Twins), 3D printing, machine learning, and artificial intelligence [8]. Therefore, it is interesting to analyse the collected papers from the point of view of the research project (i.e., BIM and Digital Twin applications) and from a broader range, thus including other Construction 4.0 technologies. Table 6 shows the data retrieved regarding the first perspective (including openBIM formats), whereas Table 7 shows the broader approach.

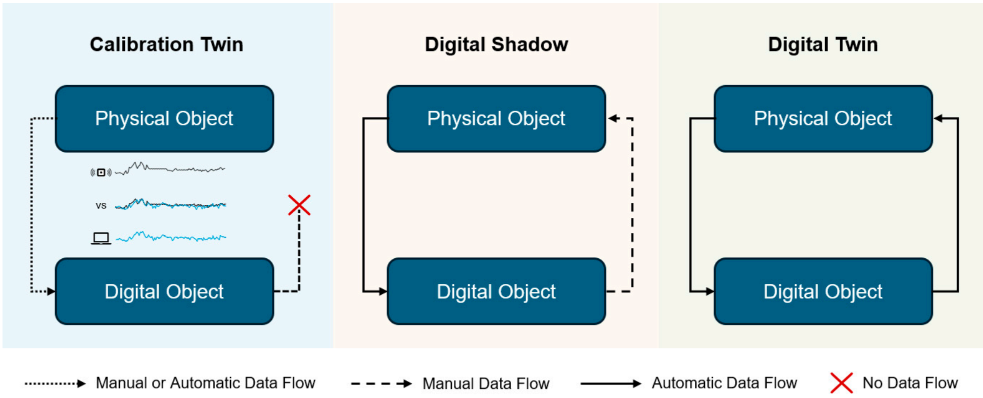

Figure 4. Digital twinning definitions. Adapted from [147–149].

Table 6. BIM and Digital Twin usage.

BIM?	IFC?	Digital Twin?	Number of Articles	References
Yes	Yes	No	8	[28,86,90,97,100,103,121,137]
		Yes	1	[110]
	No	No	38	[4,10,11,64,84,85,87–89,91–93,95,96,98,99,101,102,104–106,113,114,117,119,122,127–130,132–136,138,141,142]
		CT	3	[9,131,139]
		DS	5	[94,123,125,126,140]
		Yes	6	[107–109,112,120,124]
No	No	CT	2	[115,116]
		DS	2	[111,118]

BIM—Building Information Modelling; IFC—Industry Foundation Classes; CT—Calibration Twin; DS—Digital Shadow.

Table 7. Other technological applications.

Other Technologies?	Which?	Occurrences	References
Yes	BEM	19	[4,9,64,85,95,96,100,113,115,116,119,123,127,128,131,133,135,136,139]
	Sensors	18	[4,9,94,107–109,111,112,115,116,118,123,125,126,131,138–140]
	LCA Tools	13	[85,89,99,103,104,113,114,127,131,132,134–136]
	Automated Design Tools	12	[28,84,86,87,90,93,97,106,117,119,128,135]
	RFID Tags	8	[107–112,120,124]
	Worker's Monitor Devices	6	[107–109,111,112,124]
	Optimisation Algorithms	5	[90,93,117,119,141]
	Smart Home	5	[4,94,118,123,131]
	3D Printing	4	[28,84,97,124]
	FEM	4	[84,100,136,141]
	Game Engine	4	[112,124,130,142]
	Machine Learning	4	[86,93,96,102]
	2D CAD	3	[88,91,141]
	XR	3	[105,112,142]
	Blockchain	2	[110,120]
	CNC Machines	2	[138,141]
	Off-Site Robots	2	[124,129]
	Rule Checking Algorithms	2	[10,121]
	Data Mining	1	[96]
	Drone	1	[9]
	GIS	1	[105]
	Laser Scanning	1	[122]
No	-	5	[11,92,98,101,137]

CAD—Computer-Aided Design; XR—Extended Reality (virtual, augmented, and mixed); GIS—Geographic Information System.

3.3.1. BIM Modelling and Digital Twinning Applications

Through analysis of the collected information, it is possible to observe that most papers essentially focus on creating BIM models; however, the interest in aiming to create at least a "Calibration Twin" is noticeable. Seven Digital Twins were identified, all implemented under Hong Kong's modular integrated construction context [107–110,112,120,124]. It was found that there is a clear prominence of studies monitoring in real-time the full construction phase of buildings in Hong Kong (five high-rise [107–111] and one multifunctional [120]), from the off-site assembly, module transportation, and then for on-site construction. Moreover, there is also the case of Li et al. [112], which only focused on the on-site construction phase and also applied to a high-rise building in Hong Kong. In these studies, RFID (Radio-Frequency Identification) tags were frequently used to update the building's digital model, aiming to decrease human errors and support resource management, thus enhancing energy efficiency. Wearable monitoring devices were also used by workers [107–109,111,112], as well as the implementation of blockchain technology for smart contracts [110,120]. It should be noted that this methodology is not Digital Twin exclusive, as one of the examples [111] corresponds to a Digital Shadow, which is a step below a Digital Twin [147,148]. This case is classified as not having BIM despite using digital platforms to plan, schedule, and execute modular construction management tasks.

The Digital Twins previously mentioned presented a low level of maturity as, despite depicting characteristics of bidirectional data flow, these were only implemented to assist during a non-autonomous decision-making process by emitting alerts or, in the case of Li et al. [112], by proposing optimised crane paths to the operator. According to Sugiyama et al. [150], these cases correspond, respectively, to levels 2 and 3 regarding Digital Twin autonomy on a scale of 4. As such, only one article was found addressing the full Digital Twin realisation by using autonomous actuators for this purpose, corresponding to the study of Jiang et al. [124]. However, it is only a small-scale experiment that replicates the bidirectionality between the digital environment and the on-site activities [124]. RFID tags were used to update the digital model of the building, integrating IoT with BIM and using a robotic arm to place small 3D-printed modules that simulate prefabricated modules. Furthermore, the study replicates wearable monitoring devices for workers—an approach known as "Worker 4.0" [151].

In addition to the previously mentioned cases, more examples of Digital Shadows are identified in this literature review. Both studies of Faraj et al. [125,126] use monitoring data to assess the thermal comfort [125,126] and energy [125] conditions of their prototypes for different use cases of phase change materials (PCM). A similar process is followed by Moga et al. [140] to evaluate the thermal and energy performance of their prototype, aiming at reaching the nZEB classification. Meanwhile, Colistra [94] and Jin et al. [118] follow a different approach by implementing real-time monitoring devices to create smart homes, which allows remote senior healthcare monitoring. Studies suggest that, indeed, smart homes provide great benefits regarding continuous medical care by allowing constant monitoring of senior citizens by the local health services [152], including possible falls [94,152,153] and chronical diseases [152].

3.3.2. Smart Homes

Apart from the cases already mentioned by Colistra [94] and Jin et al. [118] that adopted real-time monitoring devices to realise smart healthcare opportunities for senior citizens, Savvides et al. [4], Vassiliades et al. [131] and Kristiansen et al. [123] used sensors for other applications within smart homes. The first study examined optimal design strategies for prefabricated housing units, considering the context of Cyprus, and achieved a nearly-Zero Energy Building (nZEB). Sensors were used to record relative environmental parameters and passive elements in addition to heating, cooling, and lighting components. Thus, it is possible to regulate these elements by installing automation systems, optimising operational efficiencies, and reducing losses to a minimum. Vassiliades et al. [131] examined the inclusion of integrated hybrid photovoltaic/thermal solar systems in a modular housing unit, focusing on multiple aspects such as thermal comfort and energy consumption. Sensors were suitably placed to measure the environmental temperature, the indoor air temperature, and the air outlet temperature (on the top of the air gap). The hybrid system contains ventilation flaps, which are then automatically activated/deactivated based on the temperature values measured by those sensors. Finally, Kristiansen et al. [123] studied their modular container prototypes intending to achieve independence from the electrical grid (thus, aiming to achieve an off-grid building), simulating their conditions for other climates besides the original one in China. In this case, the authors implemented an open-source platform for home automation so that the installed smart home devices could be controlled remotely, for example, to schedule when to turn on the air conditioning unit according to the internal temperature. It should also be mentioned that the building analysed by Antwi-Afari et al. [114] follows a similar logic to the previously mentioned ones by allowing remote or automated control of the air conditioning units, the lighting and the shading systems. Nonetheless, this information is not directly stated in the publication but only in the catalogue of the study's partner company.

3.3.3. "Calibration Twins"

Besides Ding et al. [111] and Jin et al. [118], two more articles did not address BIM modelling. Tong et al. [115] studied the effect of insulation thickness on heating energy consumption and its corresponding carbon emissions for containers used for the 2022 Winter Olympic and Paralympic Games, which were later recycled and given new uses. Wang et al. [116] analysed a temporary disaster-relief modular unit from a building passive cooling solutions optimisation perspective. Both papers used temperature sensors to collect real-time data. Then, by creating BEM models of the respective buildings in EnergyPlus, they validated the simulated values based on the measured data; therefore, these are classified as "Calibration Twins".

Unlike the previous examples that did not implement BIM in their workflows, other authors opted for BIM-based "Calibration Twin" methodologies, all for BEM analysis [9,131,139]. In particular, Vassiliades et al. [131] and Pérez-Valcárcel et al. [139] collect real-time environmental data to calibrate and validate their models, whereas Delgado et al. [9] opted for a different approach. The authors used aerial drone photogrammetry to collect the building's geometry for "as-is" BIM modelling so that BEM-based thermal comfort simulations could be performed afterward based on a BIM-to-BEM approach. Then, experimental monitoring results were compared with those obtained through simulating on DesignBuilder.

3.3.4. Reality Capture Technologies

Apart from the aerial photogrammetric-based BIM-to-BEM case of Delgado et al. [9] previously mentioned, Tan et al. [122] also used reality capture equipment: a laser scanner. This method was implemented off-site to collect as-built geometric data so that a Scan-to-BIM approach could be followed. The BIM models of bathroom pods and piping elements were used for further comparison with quality standards.

3.3.5. Automated Design Applications

Machine learning algorithms have been used to automate modular housing design generation [86,93,102], including for client-engaged collaborative design, addressing client's customisation requirements [102]. This automated modular design generation has been created directly on IFC in one of the cases [86]. Data mining tools were also implemented to study retrofitting strategies in South America [96].

Modular generative and parametric design is a common research goal in other articles assessed [28,84,86,87,90,93,97,106,117,119,128,135], which is characterised by being a computational practice that can produce design solutions with some level of autonomy [135]. In addition, some authors even implemented optimisation algorithms to select the most suitable design iteration [90,93,117,119,141]. However, authors do not privilege the use of machine learning for this process; rather, they use other types of programming (e.g., visual programming in Dynamo or Grasshopper). Apart from Ghannad and Lee's article [86], three other publications related to generative and parametric design implemented IFC in their workflows [28,90,97], nonetheless, without machine learning algorithms.

3.3.6. openBIM Applications

Most of the articles collected do not meet openBIM standards, notably by not considering the advantages of the IFC (Industry Foundation Classes) format in their workflows. ISO 16739-1 [154] defines IFC as "an open international standard for BIM data that are exchanged and shared among software applications used by various participants in the construction or facility management industry sector". In summary, it is an open standard for BIM data, digitally describing the built environment and its relationships [155]. There is an official extension of the IFC data model to support prefabricated building construction, known as IFC4precast [156–159], focusing on exchanging geometric information to manufacturing execution systems (MES) for automated production.

Apart from the examples already addressed for automated design applications, Jiang et al. [110] used IFC to exchange information between a construction's stakeholders through blockchain, while Su et al. [100] implemented this open format to export a building's BIM model to structural analysis software (based on FEM—Finite Element Modelling). In this context, Ramaji et al. [137] went further by developing an IDM (Information Delivery Manual) to stipulate the rules to follow in the data exchange process between the architectural and structural engineering teams, in addition to implementing an MVD (Model View Definition) specifically for modular buildings. Sanchez et al. [90] adopted strategies to use IFC properties correctly and then further extended the IFC schema for disassembly planning purposes (considering the DfMA methodology) and for dimensional variation analysis of the prefabricated elements. In a recent study [160], the authors intended to address this purpose by creating an MVD for building disassembly tasks.

Sun and Kim [121] proposed an automated checking system for modular BIM object quality verification. This IFC-based rule compliance code checking was tested using bathroom pod models with Singapore's guidelines. Xu et al. [103] proposed an automatic BIM-based LCA methodology through the IFC file format to automate embodied carbon assessment of prefabricated buildings. Finally, He et al. [28] programmed a Dynamo script to generate geometry models for posterior 3D printing modular housings, using IFC to convert the model to a specific format for 3D printing (.stl). The authors also note the importance of open standards (namely the IFC) to support design and production automation, discussing the IFC4precast entities. They are not the only authors implementing IFC to export to suitable 3D printing file formats, as it was also applied to a residential prototype in Chile [97].

3.3.7. Automated Manufacturing Tools

Based on the selected articles, it is possible to conclude that there is an interest in streamlining the off-site prefabrication process, hence the adoption of technologies such as 3D printing [28,84,97,124], CNC machines [138,141] and also off-site robots [124,129]. In addition to the 3D printing articles already addressed, it is worth remembering that Jiang et al. [124], one of the Digital Twins identified during this literature review, also uses 3D printing techniques for the small-scale modules (that emulate prefabricated modules), which are placed with the aid of a robot arm. Also, according to Oorschot and Asselbergs [129], the sustainable and customisable modular solution "Uuthuuske" has the particularity of being built by robots during production.

Zhang et al. [84] also implemented 3D printing in their workflow, creating a parametric design for these kinds of applications based on a visual programming script (in Grasshopper). Contrary to He et al. [28] and García-Alvarado et al. [97], who used cement, Zhang et al. [84] opted for traditional Moroccan rudimentary construction materials. Therefore, earth was the chosen material, which is locally sourced, low-cost, thermally efficient, and sustainable. By printing compressed earth blocks to create the building, attention was also given to FEM (Finite Element Modelling) analysis.

Wasim and Oliveira [141], in turn, intended to optimise the DfMA-based structural design (using FEM for that) of a modular bathroom pod, as well as its off-site construction process with CNC machines (Computer Numeric Control), enhancing efficiency and precision. These machines have also been adopted to streamline the DfMA-based modular digital fabrication process for temporary usage in catastrophe scenarios [138].

3.3.8. Finite Element Modelling (FEM)

As a crucial tool for structural analysis, FEM has been implemented in some publications for this purpose. Su et al. [100] adopted IFC to export their building's BIM model for structural analysis software, thus, allowing for a comprehensive FEM study to evaluate the seismic performance and stress of the modular building structure. As already mentioned before, Zhang et al. [84] studied the use of compressed 3D-printed earth block construction methods. Therefore, the authors also had to analyse the structural integrity of the building and not only its ecological benefits. In another instance, Wasim and Oliveira [141] aimed to optimise the design of a modular bathroom pod based on DfMA, employing FEM for structural evaluations. Moreover, when studying their sustainable timber–cork modular system for lightweight temporary housing, Barreca et al. [136] also had to consider this kind of structural analysis due to the possible seismic risks. In addition, this study also focused on LCA and BEM assessments, which are some of the most explored areas identified in the review.

3.3.9. Game Engines and Extended Reality

Extended reality (i.e., virtual, augmented, and mixed reality) has been identified as one of the technologies implemented for modular construction studies, mostly based on game engines. The exception is Gan et al. [105], which integrated BIM and virtual reality (VR) for interactive aerodynamic design and wind comfort analysis of modular buildings in Singapore, including CFD software (Computational Fluid Dynamics). It is worth noting that the authors create their BIM models through visual programming (Dynamo) by providing data from GIS (Geographic Information Systems, in this case OpenStreetMaps). However, not all articles that implemented game engines adopt extended reality strategies. Ezzedine and García de Soto [130] used BIM allied to a game engine (Unity, as in all the other cases) to manage and coordinate the design, production, transportation, and construction teams working on modular projects. As such, this study shows that game engines provide a rapid and cost-effective tool for developing digital solutions for modular construction projects. In addition, Jiang et al. [124] implemented a game engine platform to connect the physical and the digital environments to display their Digital Twin.

As in the case of Gan et al. [105], O'Grady et al. [142] also opted for VR, although, contrary to the previous one, using a game engine for this purpose. The authors presented a VR experience of a prototype (turned into a research centre of an Australian university) in which it is possible to explore the circular economy strategies implemented during the construction of the modular building. Li et al. [112] presented a different approach by being the only study to adopt augmented reality (AR) in their workflow regarding crane path optimisation planning for prefabricated construction, in which the crane operators wore AR glasses as a guide for that purpose.

3.3.10. BIM Applications Without Additional Technologies

From the collected articles, five did not use additional technologies other than BIM or towards a Digital Twin. Instead, Lee and Kim [11] explored BIM for scheduling, material quantity take-off, and quality assessment for modular apartment projects, using a similar approach to Salama et al. [92], who implemented BIM for cost and time management of the modular construction's off-site and on-site activities. Cui et al. [98] created a BIM library to enable module and furniture customisation, whereas Shao et al. [101] elaborated a sustainable architectural design for residential and affordable housing in rural areas, including several environmentally friendly strategies (such as renewable energy resources and using recycled materials). Finally, and as already mentioned in this section, Ramaji et al. [137] addressed important openBIM concepts by developing an IDM (Information Delivery Manual) to stipulate the rules to follow on the data exchange process between the architectural and structural engineering teams in addition to implementing an MVD (Model View Definition) specifically for modular buildings. This process has been validated through a student residence case study.

3.3.11. General Digital Remarks

The importance of programming in digital modular construction is noticeable, as already addressed in this section. Other examples include being capable of automatically generating quantity take-offs and shop drawings based on 2D CAD that are transformed into 3D BIM models through VBA-based tools [88], promoting collaborative BIM and ontology-based DfMA modular design processes with multiple algorithms [10] or by using visual programming (such as Dynamo) with BIM to estimate parameters for the LCA analysis of a building [113].

Despite the strong contribution of programming in general, BEM, sensors, and LCA constitute the most common practices identified in the literature. The combination of these topics has already been discussed in this section; nonetheless, it is worth noting its importance for modern modular construction, in which digitalisation and sustainability are key factors. Moreover, from a broad perspective, IoT is the most used digital technology, encompassing sensors, RFID tags, and worker's wearable devices. In fact, there has been a significant increase on using IoT in the building prefabrication industry, in addition to the growth of artificial intelligence (AI) methods [36]. The example of Ghannad and Lee [86], included in this review, implemented coupled generative adversarial networks (CoGAN) that, with some inputs, generated modular building layouts, although they did not use IoT in their study.

3.4. Building Construction Solutions

After assessing the digital technologies implemented in the selected articles, the focus must shift toward the case studies' building construction solutions, including passive and active systems. Therefore, this section is vital to understanding modern-day construction tendencies, which may be useful for further investigation regarding this topic and the research consortium's decisions further ahead.

Table 8 provides an overview of the case studies' information, distributed by their respective Köppen–Geiger climate classification [161]. This analysis encompasses the construction materials, including the insulation material and thickness, in addition to the building envelope's thermal properties. It should be noted that for this assessment, every article that stated where the case study was located was grouped according to this climate classification, even if their climate zone was never mentioned in the text. Also, an article can have multiple case studies, so each one is assessed individually, including the conceptual studies in different climate zones. If an estimated location could not be assessed from an article, it was not considered for this categorisation and, thus, grouped as "N/A" (not available). That is the case when a country has multiple climate zones, and it is impossible to estimate in which the building could potentially be implemented. The extended version of this dataset is available in the Supplementary Materials, particularly Tables S1.1 and S1.2.

Table 8. Summary of the case studies' building characteristics by climate zone.

Climate	Climate Zones	Panels	Insulation	Framing	External Walls		Floor		Roof		Windows	Doors
					U_{ext_walls} ($W/m^2{\cdot}K$)	Insulation (cm)	U_{floor} ($W/m^2{\cdot}K$)	Insulation (cm)	U_{roof} ($W/m^2{\cdot}K$)	Insulation (cm)	$U_{windows}$ ($W/m^2{\cdot}K$)	U_{door} ($W/m^2{\cdot}K$)
A (Tropical)	Af	Precast Concrete	-	-	-	-	-	-	-	-	-	-
	Aw	(Multiple)	PUR + Rock wool	Steel	0.73	10	-	-	0.43	10	-	-
B (Arid)	BSh	(Multiple)	PUR	Steel	0.51	10	0.32	-	0.35	10	2.00	-
	BSk	Metal	PUR + Mineral wool	Steel	0.20	9	0.47	4.8	0.18	10.3	1.77	1.77
	BWh	Fibreglass	PUR	Steel	-	-	-	-	-	-	-	-
C (Temperate)	Csa	Wood	(Multiple)	Steel	0.38	12.5	0.17	7.7	0.30	12.5	3.13	3.73
	Csb	Wood	Rock wool	(Multiple)	0.40	11.9	0.34	9	0.27	14.3	2.56	3.37
	Cwa	Precast Concrete	EPS + Rock wool	Reinforced Concrete	0.72	5	3.82	-	0.44	7.5	5.78	-
	Cwb	Metal	PUR + Mineral wool	Steel	0.18	5.5	0.56	2	0.18	5.5	1.76	1.76
	Cfa	Metal	PUR + Mineral wool	Steel	0.22	12	0.38	10.8	0.18	14.3	1.32	1.46
	Cfb	Wood	(Multiple)	Steel	0.34	21.8	0.32	8	0.25	16.5	1.87	-
D (Continental)	Dwa	Metal	PUR + Mineral wool	Steel	0.22	7.9	0.47	3.7	0.25	7.9	1.77	1.77
	Dfa	Wood	-	Wood	-	-	-	-	-	-	-	-
	Dfb	Wood	-	Wood	-	-	-	-	-	-	-	-
N/A	N/A	Wood	(Multiple)	Steel	-	-	-	-	-	-	-	-
Average		**Wood**	**PUR + Mineral wool**	**Steel**	**0.33**	**11.7**	**0.54**	**6.7**	**0.25**	**11.3**	**2.15**	**2.28**

NOTE: The U-values for the floor and windows in the Cwa climate zone are clear outliers in this study, corresponding to a non-insulated floor of a temporary house and simple-glazing windows, respectively. If these values were to be excluded, the global average would be U_{floor} = 0.38 $W/m^2{\cdot}K$ and $U_{windows}$ = 2.00 $W/m^2{\cdot}K$ instead.

By analysing Table 8, Tables S1.1 and S1.2, it is possible to conclude that most case studies are located in temperate climates, mostly with Mediterranean characteristics. Moreover, wooden-panel construction is prevalent, particularly for temperate and continental climates, in addition to the generalised adoption of steel panels, including those that reuse maritime containers. Apart from wood and steel, precast concrete has been used several times, mainly for buildings located in dry winter humid subtropical climates (Cwa).

There is a clear predominance regarding steel structures, with reinforced concrete also being vastly implemented for high-rise construction and a broad prominence of wood for low-rise residential buildings up to two storeys and temporary housing. It is worth noting that structural steel is essentially employed in actual modular buildings, whereas reinforced concrete solutions are more commonly used for hybrid construction (panelised and volumetric), which is coherent with the literature [162]. In fact, the vast implementation of steel-framed construction is highly beneficial for modular construction based on the DfMA principles. In particular, according to this concept, steel-framed construction allows for great potential for material reuse [163]. Moreover, it presents adequate structural behaviour, including under seismic actions, as well as being a durable material and allowing industrial production [101].

Multiple insulation materials have been identified, mostly of mineral and synthetic origins. Considering the information gathered in Table 8, the buildings under analysis have, on average, exterior walls with an insulation layer of 11.7 cm, whereas the floor has 6.7 cm, and the roof has 11.3 cm. Climate zones without a dry season with hot or warm summer (Cfa and Cfb), as well as Mediterranean climates (Csa and Csb), were the ones that presented the highest insulation layer thickness, while temperate climates with dry winter (Cw category) followed a contrasting logic, thus, being the ones with the lowest insulation thickness. Nevertheless, temperate climates are the ones that present, on average, a thicker insulation layer, whereas continental climates feature thinner layers, although this observation may be skewed since most studies conducted in continental climates are of an experimental nature. According to Tavares and Freire [85], this should be the opposite: continental climates must have higher levels of insulation than Mediterranean climates. Also, the authors state that tropical climates must have lower levels of insulation in comparison.

Additionally, it was found that buildings in humid subtropical climates (Cfa) have the lowest thermal transmittance coefficient for all construction elements except for the walls and floor; nonetheless, the walls are still ranked among the lowest too.

Buildings situated in Mediterranean climates (Csa and Csb) present the highest values for glazing elements. The only exception is the single case under the Cwa climate, which has the highest U-value for the windows.

Regarding the overall average building envelope, the mean U-value of the exterior walls is 0.33 $W/m^2{\cdot}K$, 0.54 $W/m^2{\cdot}K$ for the floor, and 0.25 $W/m^2{\cdot}K$ for the roof. The average U-value for the windows is 2.15 $W/m^2{\cdot}K$ and 2.28 $W/m^2{\cdot}K$ for the doors.

In addition to the building's information already covered, it is important to understand the strategies and technologies employed to enhance the energy efficiency and sustainability of these buildings. As such, Table 9 provides a summary of the active and passive solutions implemented in the buildings under study. For a more detailed dataset, please refer to Table S2 in the Supplementary Materials.

Table 9. Summary of the reported building solutions per article.

Systems	Solutions	Reported Occurrences	References
Active	HVAC Systems	15	[95,96,114,115,118–120,123,125–127,129,131,133,134]
	Photovoltaic Panels	13	[4,89,101,114,118,123,127,129,132,135,138,140,142]
	Solar Thermal Systems	7	[4,95,101,118,123,131,138]
	Heat Pumps	6	[9,85,123,127,129,131]
	Radiant Floors	6	[101,123,125,126,129,133]
	Hybrid PV/T Systems	2	[123,131]
	PCM	2	[125,126]
	Biomass	1	[95]
	Wind Energy	1	[140]
	Geothermal Energy	1	[118]
Passive	Thermal Insulation	28	[4,9,64,85,92,95–97,99,101,114–118,123,125,126,129,131–133,135,136,138–140,142]
	Direct Solar Gains	23	[4,9,64,85,95,96,101,113,114,116,118,123,125–129,131,133,134,136,140,142]
	Natural Lighting	20	[4,9,64,95,96,101,106,113,114,116,118,123,127–129,131,133,134,136,140]
	Shading Systems	16	[4,9,95,96,101,114,116,118,123,127,131,133,136,138–140]
	Natural Ventilation	16	[4,64,95,96,101,115,117,118,123,127,128,131,136,138,140,142]
	Air Tightness	11	[4,94,95,115,118,129,131,134,136,139,140]
	Water Harvesting	8	[95,101,115,118,123,135,138,139]
	Green Roofs	4	[95,99,101,127]
	PCM	4	[125,126,135,136]
	Green Wall	1	[118]
Automation Systems		8	[4,94,101,118,123,125,126,131]
Off-Grid		5	[4,101,118,123,140]

Many articles do not address the active and passive strategies; therefore, much information cannot be retrieved. Despite the lack of data, multiple active systems are addressed in the reviewed articles, with particular attention to HVAC systems (e.g., mechanical ventilation). It is important to note the great focus on renewable energy sources, such as biomass, wind energy, geothermal energy, and mainly solar energy, due to the vast implementation of photovoltaics and solar thermal systems.

Some passive solutions are scarcely detailed in the collected papers. Thermal insulation is the most commonly addressed, with materials and thicknesses listed in Table S1.2 (Supplementary Materials); however, some state their use but do not detail its characteristics (including the material). Only two publications have implemented reused or recycled insulation materials in their buildings. Shao et al. [101] implemented crop waste material—straw in this case—for the wall's thermal insulation. Moreover, Moga et al. [140] recycled PET (polyethylene terephthalate) bottles and, with its polyester fibres, the authors managed to implement recycled PET thermal wadding as a sustainable insulation solution for both walls, floor, and roof. Therefore, it can be concluded that, overall, the publications identified by this literature review do not consider recycled insulation materials for their studies despite their great environmentally friendly potential. Other potential solutions as recycled insulation materials include tyre rubber [164], textiles [165], paper [166], crop waste [167], and earthquake rubble [168], among others [169]. Also, it should be noted that no article was found implementing thermal insulation materials from animal origin (e.g., sheep wool).

There are multiple parameters to consider when choosing insulation materials, such as thermal conductivity, fire resistance, cost, durability, sound absorption, and resistance to biological dangers (e.g., insects and fungus). From a building physics perspective, all the insulation materials implemented in the case studies have similar values of thermal conductivity [170,171], although PUR and PIR foam are considered more thermal resistant [171,172]. Rock wool has an excellent fire rating, as it is non-combustible, which is an advantage compared to the other solutions' behaviour [171]. Insulation materials of synthetic nature (EPS, XPS, PUR) are not good options for building acoustics [171–173], while rock wool and cork are better for this purpose [171,172]. Moreover, synthetic materials are more impermeable than other types, such as inorganic fibrous materials (e.g., rock wool) [171,173].

From an environmental point of view, rock wool is an efficient option in terms of embodied carbon emissions and is safe for waste disposal; however, it is not a recyclable material [171–173], contrary to wood wool [173]. Synthetic materials are not the best options from the sustainability perspective for many reasons, starting from the fact that they have average values of embodied carbon [172,173]. PUR also has poor waste disposal and reuse or recycling potential, while EPS and XPS perform better on these parameters [172,173]. Cork is one of the best options among the insulation materials, as assessed from an environmental perspective. This natural material is a direct and renewable product from the cork oak tree (which is native to the western Mediterranean region), being an efficient and recyclable option [173,174]. According to Tártaro et al. [174], cork is the only building insulation material in the market with a negative carbon footprint. Despite its environmental benefits, cork is not a good option from an economic perspective [173].

In addition to cork, one more instance was identified in the literature review where vegetal-based insulation has been implemented. Shao et al. [101] opted for a local crop material: straw. As a byproduct of cereal cultivation, this material is available in large quantities and at a low cost in multiple countries [169]. Recently, Sun et al. [175] reviewed the advantages of using straw as an insulation material. The authors concluded that this unconventional building material provides multiple benefits, including from an environmental perspective, and is a favourable indoor thermal comfort solution for oceanic, Mediterranean, and humid subtropical climate zones; nonetheless, the authors noted some issues regarding humid continental climates.

Apart from natural materials such as cork and straw, one publication implemented recycled materials for building insulation. As already mentioned, Moga et al. [140] recycled PET (polyethylene terephthalate) bottles and, with its polyester fibres, the authors managed to implement recycled PET thermal wadding as a sustainable insulation solution for both walls, floor, and roof. This is a sound environmental solution, as it stimulates the local economy and emphasises material circularity principles, such as recycling and reuse. Moreover, PET has good thermal insulation capabilities [169,176], even when using fully assembled PET bottles as an insulation layer instead [176].

Phase change material (PCM) layers were implemented on four occasions. Research on temporary housing applied these materials on external wall panels [135,136], whereas experimental studies with prototypes tested these layers in multiple configurations, including their use on the floors and on the external walls [125,126]. The PCM layer acts as a thermal energy storage system, storing the heat flow during liquefaction and then discharging the latent heat when the temperature drops, thus solidifying the PCM [136]. As such, according to Faraj et al. [126,177], this kind of material is a promising option towards nearly-Zero Energy Buildings (nZEB). While the material itself is not mentioned in these cases, there are studies where potential options have been discussed, such as macro-encapsulated PCM plates containing coconut oil and paraffin wax [126]. All case studies identified implemented PCM as a passive system [125,126,135,136]. Nevertheless, Faraj et al. [125,126] went further by using PCM coupled to radiant underfloor heating systems as an active solution instead. It should be noted that despite its varied applications, particularly under the building's domain, using PCM is not yet a common practice in the AEC sector [178].

Four examples of buildings with green roofs were found in this literature review: three residential [95,101,127] and one multi-storey [99]. Green roofs are a type of construction that allows vegetation growth, aiming at improving the energy performance of the building while mitigating urban heat island effects [179,180]. Green roofs can capture harmful particles, thus improving air quality by purifying it [180]. Moreover, green roofs can collect rainwater for further use [101,179,180]. The substrate then filtrates the water, which absorbs pollutants from the rainwater, thus improving water quality [101,180]. Afterward, the water is purified for human use (e.g., sanitary discharges, gardening). Two articles that implemented green roofs also implemented rainwater harvesting strategies for further water reuse [95,118]. Nonetheless, this method is not exclusive to buildings with this roof typology, as six others are reusing this water [115,118,123,135,138,139].

One article addressed green walls (indoor in this case), which were applied to an area consisting of an indoor courtyard [118]. This passive solution enables the indoor building temperature to be regulated naturally, reducing heating and cooling energy loads [118,179] and providing an interesting strategy for building acoustics [179]. Moreover, there is also one instance where the authors opted to use a solar chimney, which improves natural ventilation during summer by absorbing heat produced by solar radiation, whereas, during winter, the solar chimney block can be converted to thermal insulation by closing the air gaps. As such, the solar chimney benefits natural ventilation, reducing the need for mechanical ventilation and improving the air renewal rate [101].

Hence, it is evident that natural building ventilation is of utmost importance. Indeed, natural ventilation should be considered since the design stage, as it offers benefits regarding improving the air quality through a higher rate of air renewal and consequent reduction in CO_2 levels, in addition to reducing electrical power consumption, especially for buildings containing mechanical ventilation [96]. As shown in Table 9, multiple authors applied natural ventilation in their case studies, which is consistent with the modular construction literature [4].

Apart from the passive solutions addressed in the previous tables, it is worth noting four cases that implemented ventilated façades in their studies, all from temperate climates with hot or warm summers [95,138–140]. This kind of façade is useful for both warm and cold areas, which, for the purposes of these publications, prevents heat accumulation and regulates it, thus reducing the energy used for cooling. Moreover, ventilated façades avoid condensation issues and can eliminate thermal bridges [179].

Other passive commonly adopted solutions identified in the case studies are incorporating natural lighting and direct solar gains while using shading systems to regulate the building's performance on those gains and heat loss. Furthermore, the importance of thermal insulation and airtightness is noticeable. Therefore, this analysis is consistent with the current literature [4].

Interestingly, no article explored automated solutions for solar radiation control, such as thermochromic windows or adaptive solar façades. Thermochromic windows are a high-performance dynamic glazing system created to reduce heat loss by controlling the incoming solar radiation, leading to energy savings and minimising solar gains in the summer while maximising them during winter [181,182]. Adaptive solar façades are dynamic shading systems that integrate robotics with sustainable energy performance, increasing renewable energy production through building-integrated photovoltaics and enhancing occupant comfort by automatically regulating incident solar radiation and daylight distribution [183–186]. An example of this kind of adaptive façade is the Al Bahar Towers in Abu Dhabi, United Arab Emirates [186,187]. As already discussed in Section 3.3, most of the automation systems mentioned in the selected papers are related to HVAC systems and lighting from a "smart home" perspective [4,94,118,123,131], such as turning on/off the mechanical ventilation based on temperature recordings. This same logic is followed by Faraj et al. [125,126] to turn on/off the radiant underfloor heating system present in their prototype through indoor temperature recordings. In turn, Shao et al. [118] implemented manual remote controls to regulate the angle of their shading systems. Nonetheless, this approach differs from the one adopted for adaptive solar façades, as the process is not automated.

Five publications developed a modular building that can operate autonomously off-grid [4,101,118,123,140] through a combination of active and passive building solutions, predominantly by implementing renewable energy resources (particularly solar, wind, and geothermal energy). In addition, some authors opted to use recycled materials whenever possible [4,101,140]. It should also be noted that only three of these articles recognised that they could fulfil the nZEB requirements [4,118,123].

Two articles proposed foldable building solutions for emergency temporary housing [117,139]. The aim is to provide a low-cost solution that is transportable and easy to assemble by non-qualified workers. In addition, both care about sustainability by promoting low-energy-consumption buildings based on circularity principles (such as DfMA). Sabaghian et al. [117] apply their method to the Iranian desert context (BWh climate), while Pérez-Valcárcel et al. [139] study their prototype at the University of A Coruña (Csb climate).

Another important concept that was possible to understand during this analysis was the concept of bioclimatic architecture. Thus, some authors address this topic of developing building solutions according to the location's climate; for example, Shao et al. [118], who implemented multiple active and passive systems specifically for West China's rural areas, mentioning that these could be adapted to different building locations and climates. Other publications clearly show those adaptations. For example, in the off-grid modular building of Kristiansen et al. [123], the authors implemented different active systems according to the climate, in this case by using PV/T systems, floor heating, and a generator specifically for cold climates (in this case, BSk and Dwa) to increase the heating load. Najjar et al. [64] addressed bioclimatic architecture differently by designing optimal ventilation opening dimensions based on each Brazilian climate zone toward energy efficiency and sustainability optimisation. Moreover, some authors study different thermal insulation thickness options based on where their buildings will be located [85,115,135].

Finally, it should be noted that no study has addressed polar climates (category E). Buildings in such severe cold climates must be exceptionally well insulated, airtight, and implement highly efficient ventilation systems with heat recovery [188,189]. Passive buildings in polar climates must focus on minimising heat loss prior to addressing the maximisation of heat gains [188]. Moreover, considering that there is no natural lighting at some of these latitudes for several months, the main renewable energy source to consider should be wind rather than solar energy [189].

3.5. Building Sustainability

The European Union strives to be climate-neutral by 2050; however, significant changes have to be made, especially for the construction sector, as it has a massive impact on energy consumption and greenhouse gas emissions [29–32]. Indeed, building sustainability and environmental protection are among the main pillars of the "R2U" research project [33]. Therefore, it is interesting to collect information about this topic in articles. The literature suggests a general upward trend in the interest in this aspect of modular construction [19]. Indeed, prefabrication, in general, is beneficial towards sustainability goals from assembly to disassembly, contributing to a lean construction environment by better controlling material resources, including less waste, reducing energy consumption, greenhouse gas emissions, and embodied carbon [4,19,103].

Sustainability lies in three pillars: environmental, social, and economic [13,190]. These are the basis for construction sustainability certification ratings tools, such as LEED, BREEAM, and SBTool, as well as for the European Framework for Sustainable Buildings, known as Level(s) [190]. Despite their significance for this topic, only one of the collected articles addressed these certifications [99]. Instead, they apply life cycle assessment (LCA) tools, which are widely used to evaluate building sustainability performance [19]. The principles and framework for conducting an LCA are defined in ISO 14040 [191], while ISO 14044 [192] defines its requirements and guidelines. For buildings, EN 15978 [193] and EN 15804+A2 [194] are the standards used to calculate this environmental performance. Furthermore, EN 15643-1 [195] defines the life cycle stages of a building, and it is based on these that the carbon emissions are calculated [196]. Figure 5 summarises this information.

LCA is only concerned with environmental assessments; therefore, it does not provide a complete sustainability evaluation [114,197]. To correct this, in 2009, the United Nations Environment Programme (UNEP) defined guidelines for social and socio-economic life cycle assessments (S-LCA) [197–199], complementing in 2020 for social–organisational life cycle assessments (SO-LCA) [199].

For this literature review, the environmental approach was considered the most relevant to the project's ambitions. Thus, the collected data provide evidence of this perspective. Table 10 provides a summary of the environmental sustainability indicators categorised by climate zone, offering an overview of the performance within different climatic contexts. Purposely, it was decided not to include averages for the global warming potential (GWP) as articles have multiple system boundaries and assumptions (e.g., the life cycle stages considered for the analysis); therefore, these cannot be directly compared. In turn, Table 11 focuses on sustainable building solutions, emphasising the efforts towards environmental protection. Additional extended information can be found in Table S3 of the Supplementary Materials.

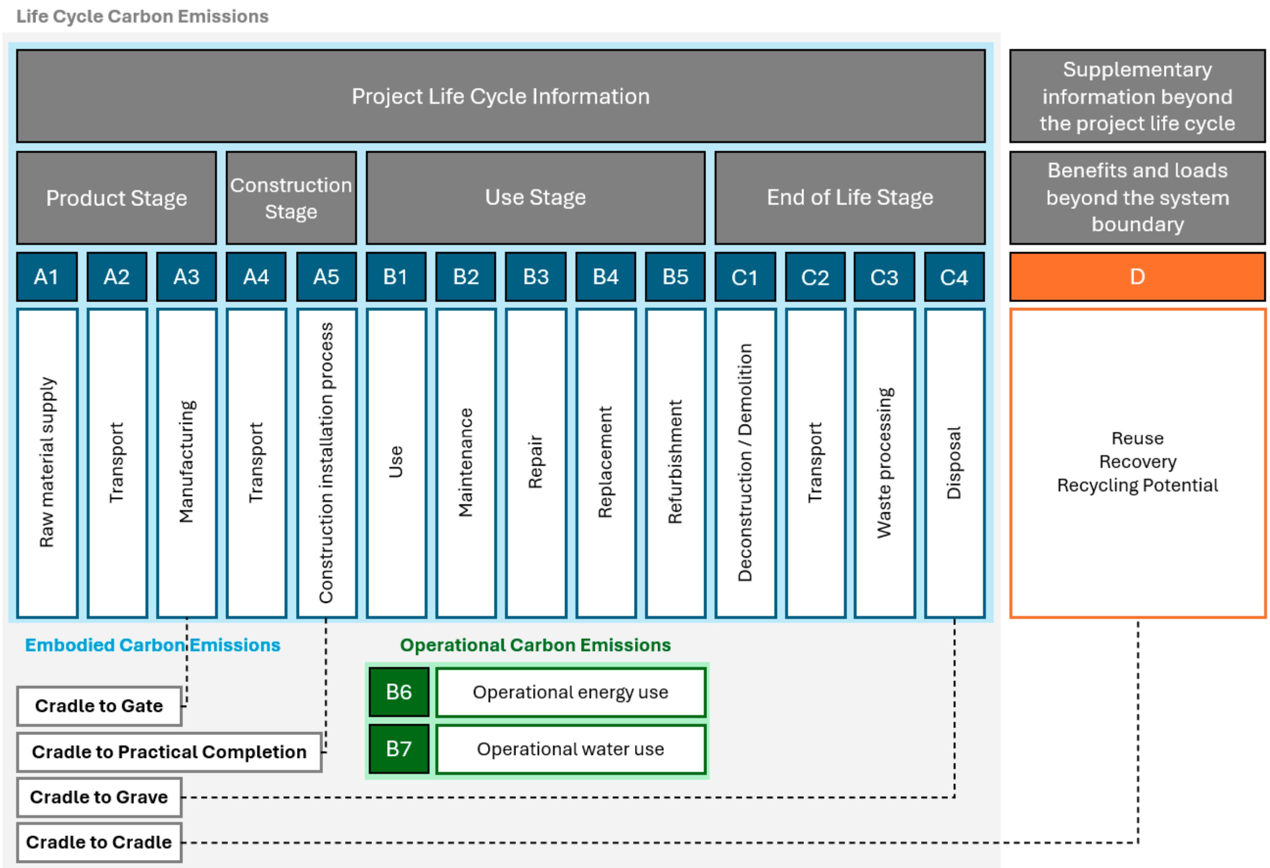

Figure 5. Building life cycle stages, including carbon emissions. Based on [193–196].

Table 10. Summary of the case studies' environmental indicators by climate zone.

Climate	Climate Zones	Energy Use (kWh/m²/Year)	Renewable Energy Sources
A (Tropical)	Af	-	-
	Aw	50	Natural Gas (*)
B (Arid)	BSh	71	Solar + Natural Gas (*)
	BSk	129	Solar
	BWh	-	-
C (Temperate)	Csa	53	Solar + Natural Gas (*)
	Csb	56	Solar + Biomass + Natural Gas (*)
	Cwa	128	-
	Cwb	116	Solar
	Cfa	124	Solar + Wind
	Cfb	100	Solar + Natural Gas (*)
D (Continental)	Dwa	171	Solar + Wind + Geothermal
	Dfa	-	-
	Dfb	-	Solar
N/A	N/A	-	Solar
Average		**100**	**Solar**

NOTE (*): According to EN 15804+A2 [194], natural gas is not considered a renewable energy resource but rather a fossil fuel. However, the European Union considers natural gas as green energy in some circumstances [200,201].

Table 11. Summary of the articles' sustainable building solutions.

Environmental Indicators	Solutions	Number of Articles	References
Bioclimatic Strategies	Green Roof	4	[95,99,101,127]
	Green Wall	1	[118]
	Water Reuse	7	[95,101,115,118,123,138,139]
Material Circularity	Reused Materials	5	[100,115,123,136,142]
	Potential of Reusing Materials	6	[94,99,133,138–140]
	Recycled Materials	6	[4,101,115,129,140,142]
	Potential of Recycling Materials	6	[99,123,132,133,136,139]
Renewable Energy Sources	Solar	13	[4,89,95,101,115,118,123,131, 132,135,138,140,142]
	Wind	2	[115,140]
	Biomass	1	[95]
	Geothermal	1	[118]
	Natural Gas (*)	2	[9,85]
Building Classification	nZEB	5	[4,115,118,123,132]
	Off-Grid	5	[4,101,118,123,140]

NOTE (*): According to EN 15804+A2 [194], natural gas is not considered a renewable energy resource but rather a fossil fuel. However, the European Union considers natural gas as green energy in some circumstances [200,201].

All the articles collected that have any environmental indicator (and thus, eligible for this evaluation) have the building as its assessment level, as can be seen in Table S3 (Supplementary Materials). Some authors expand this approach by including other levels [85,89,103,104,113,114,132,134]. For instance, Xu et al. [103] analysed the embodied carbon emissions until practical completion based on a five-level framework: materials, components, assemblies, flats, and the building (in this case, a prefabricated high-rise in Hong Kong). The authors used an automatic openBIM-based LCA methodology to automate this embodied carbon assessment. This steel framing building built with precast concrete panels, in addition to modular kitchen and bathroom pods, has a global warming potential of 561 kg CO_2e/m^2, which is similar to other assessed high-rise constructions [113,114]. The curtain wall building of Arslan et al. [134] is the one with the most global warming potential (GWP) among the analysed buildings since the concrete structure was cast in situ, not taking advantage of the environmental prefabrication benefits.

The building with the least GWP is a dwelling located in Hungary, clearly benefitting from being built with wooden panels and taking full advantage of sustainable active and passive strategies, including using renewable energy [127]. This study adopted a "Cradle to Cradle" philosophy, focusing on the recycling and reusability potential as well as sustainable materials (particularly wood) to achieve carbon neutrality. This was the only identified article that managed to reach this threshold.

It is important to note that the analyses of the quantitative environmental indicators addressed here have different system boundaries and assumptions. This includes which building life cycle stages are considered for the analysis and the buildings' lifespan. For example, the multi-storey building of Budig et al. [104] corresponds to the second least GWP identified. Nevertheless, despite the clear advantage of being built with wooden panels, this value is due to the fact that the article applies the LCA methodology only from a "Cradle to Gate" perspective, i.e., only considering the product stage and thus not counting the other life cycle stages of construction, which would influence this result. Another example is the difference between the building's lifespan; some consider 50 years [85] while others only consider ten years [136].

In terms of energy consumption per m^2/year, the "CASA +" of Celis-D'Amico et al. [95] is one of the best solutions analysed by benefitting from multiple passive strategies, including a green roof and rainwater harvesting systems, in addition to using renewable energy sources (solar and biomass). Moreover, one other case also implemented rainwater harvesting systems that managed to achieve low energy consumption levels and invested in renewable energy [135]. Nevertheless, the building with the least energy consumption is the study of Pibal et al. [128], which focused on BIM-based generative design for early design stages of modular multi-storey buildings, aiming to optimise energy consumption, particularly for heating purposes. No information about using renewable energy sources or circularity of materials is given. By comparing the result of this study with others from the same or similar climates, it is possible to conclude that this is an outlier, potentially due to intending to reach the Passive House certification criteria for energy consumption (inferior to 15 kWh/m^2/year) [202]. The only study analysed (prior to excluding it due to not meeting the review's inclusion criteria) that could compete with such value was an off-grid modular building based on multiple passive design strategies, automated systems, renewable energy sources (namely solar), high reusability potential and a full Digital Twin for smart energy management. This building was reported to consume 25.8 kWh/m^2/year, while emitting 14.3 kg CO_2e/m^2/year, in addition to being able to achieve positive energy net balance that could be exported to the grid, offsetting its carbon emissions and making it carbon-negative in its performance [62]. However, this modular building was developed to be a primary school classroom, thus, not following residential building's occupancy profiles, which influences the results.

By analysing Table S3 (Supplementary Materials), it is possible to evaluate some differences between similar solutions and their behaviour depending on the climate. Vassiliades et al. [131] studied thermal comfort from a use stage perspective, assessing the energy consumption of the modular building in two different locations. Bolzano (Cfb) has a colder climate than Larnaca (BSh), so the Italian unit consumed more energy for heating purposes, while the Cypriot had higher cooling loads. Ultimately, the heating loads from Bolzano surpassed the cooling loads from Larnaca, resulting in higher energy use. In turn, Kristiansen et al. [123] studied the viability of reaching energy self-sufficiency with adequate thermal comfort for five Chinese locations. For both buildings under analysis ("Base" and "Compact"), cold climates have been identified as being the most energy demanding, where the authors had to implement additional active solutions for heating purposes (e.g., radiant floors), as these locations demanded more heating loads than the other locations. Tavares and Freire [85] presented a similar logic by studying multiple locations worldwide and analysing their energy loads, as well as several environmental impact indicators. The authors concluded that continental climates resulted in higher energy demands than Mediterranean and tropical climates (which corroborates the findings of Table 10). Regarding embodied global warming potential, the values were considered relatively similar, although differences were noticed concerning operational impacts. Nonetheless, these are out of the scope of this literature review.

The containers used for the Beijing 2022 Winter Olympic and Paralympic Games [115] are the ones with the highest energy demand, particularly those located at altitude (at 2177.5 m), which is understandable considering they are located in a colder area (Dwa) compared to the ones located at the Olympic/Paralympic Village (BSk) at a lower altitude (950 m), thus, more in need to heat the units. After the end of the Games, these containers were recycled and transformed into convenience stores, hotel rooms, and so on, on a clear circular construction mindset. Using renewable energy allied to passive building solutions, these modular buildings met the nZEB criteria, although insufficient to reach independence from the electrical grid to be considered off-grid buildings.

Also, from a circular construction perspective, O'Grady et al. [142] developed a modular building prototype based on the DfMA principles that would eventually be transformed into a research centre. Contrary to other authors who only note the materials recycling and reuse potential (Table 11), O'Grady et al. [142] effectively reused 58% of the materials, particularly steel (including structural) and wood, in addition to multiple recycled materials (e.g., balcony tiles made of recycled rubber and plastic waste, or acoustic panels made of recycled PET plastic). Apart from this example, the other cases that adopted material reuse strategies are related exclusively to converting maritime containers into housing units [100,115,123,136]. It should be noted, however, that this was not the only study that opted to recycle PET plastic, as in the case of the off-grid prototype of Moga et al. [140], the authors recycled PET bottles to use its plastic fibres as a thermal insulation layer. On two more occasions, the recycled materials were applied directly into the buildings: one used recycled aggregates made from construction and demolition waste (CDW) to produce sustainable concrete [129], while the other also implemented CDW, on this occasion for the foundation blocks of a self-sufficient building [101]. Moreover, blast furnace ash, a byproduct of steel production, was also applied to the soil to be used as anti-freeze soil padding [101].

Savvides et al. [4] presented a distinct approach for their nZEB modular unit located on the outskirts of Nicosia, Cyprus. This study intended to maximise the use of recycled structural parts and construction materials in the assembly line, primarily focusing on those from aluminium and wood. Recycled elements, mostly made of OSB (Oriented Strand Board), were also used for furniture and exterior cladding finishes. The authors created a building that can operate independently from the national electricity grid by combining a sustainable approach based on a DfMA philosophy, optimal active and passive solutions, and renewable energy resources. Moreover, all modular off-grid buildings identified in this literature review [4,101,118,123,140] note the importance of implementing renewable energy sources to achieve energy self-sufficiency and complement them with passive building solutions. They all implemented solar-based active systems, with two incorporating a second renewable energy source: one implementing geothermal energy [118] and the other wind energy [140].

4. Discussion

4.1. Digital-Oriented Modular Construction

Prefabricated construction originated in the Stone Age and has been evolving ever since. In the 20th century, a modularised approach was introduced [1]. Modular construction follows a DfMA philosophy, providing many advantages to the sector from various perspectives such as social–economic, environmental, and occupational health and safety [4,9–13].

In the age of Construction 4.0, new technologies are reshaping the construction industry, enhancing productivity and efficiency in a sector known for its traditional methods and slow adoption of technological advancements and innovations [8]. Allied to modular construction, it is possible to extend the benefits of this kind of prefabricated construction further [25–27], including easier module customisation requirements [28]. Indeed, most of the papers collected in this review are focused on the design stage, where digital technologies improve modular construction's detailed design processes, reducing early-stage mistakes, improving collaborative tasks between different stakeholders, and optimising building designs [25–28].

From the articles collected during this literature review, it is possible to understand the multiple benefits of this digital integration. BIM has been deployed on several occasions; however, only a few papers have implemented an openBIM methodology [28,86,90,97,100,103,110,121,137]. More attention should be given to openBIM standards (particularly IFC) as they enhance coordination and collaboration by facilitating the interoperability of BIM models among different stakeholders [25,27,28].

There is a clear interest in integrating real-time data to connect modular buildings to their corresponding digital model. Particularly, a trend has been identified for modular construction projects in Hong Kong [107–112,120,124]. In this review, seven Digital Twins have been implemented [107–110,112,120,124], all of them related to the execution phase in the aforementioned region. RFID tags are the predominant method to update a building's digital model, in addition to the implementation of wearable monitoring devices. Digital Shadows have also been addressed seven times [94,111,118,123,125,126,140], most of them being related to BEM (Building Energy Modelling) for energy or thermal comfort simulations [123,125,126,140], two related to smart homes [94,118] and one following a similar approach to the Digital Twins [111], although without being able to reach a bidirectional data flow. Finally, five "Calibration Twins" were also identified, all related to energy or thermal comfort analysis [9,115,116,131,139].

Smart homes have been deployed five times in this review [4,94,118,123,131], with three being related to automation systems to optimise energy efficiency, particularly for heating, cooling, and mechanical ventilation purposes [4,123,131]. In addition, smart homes provide remote senior healthcare monitoring [94,118], which is fundamental for continuous medical care by allowing constant monitoring of senior citizens by the local and hospital health services [152], including possible falls [94,152,153] and chronic diseases [152]. Moreover, smart homes have some similarities with the concept of Digital Twins, although they have some differences, too. While Digital Twins and smart homes are interconnected concepts that leverage advanced technologies like IoT, artificial intelligence, and big data, they differ in scope and application. Smart homes primarily focus on user-centric automation and convenience, such as providing control via intelligent apps [118,123]. In contrast, Digital Twins extend beyond automation to include dynamic simulation and predictive capabilities, allowing for proactive problem-solving and enhanced lifecycle management. For example, Digital Twins can replicate the history of a system's data to simulate potential interventions and their impacts [203]. However, both systems aim to integrate physical and digital elements to improve efficiency and user experience. By combining these technologies' strengths, a hybrid approach could further revolutionise home automation and sustainability [204,205].

Considering the other technologies applied in the assessed studies, it is possible to conclude that generative modular and parametric designs are of utmost importance and are being vastly implemented. This computational design practice that can produce design solutions with some level of autonomy [135] emphasises the importance of programming in the context of architecture and civil engineering, in addition to the increasing relevance of artificial intelligence. For example, Ghannad and Lee [86] implemented coupled generative adversarial networks (CoGAN) that, with some inputs, generated modular building layouts. Indeed, the use of convolutional neural networks (CNN) and generative design networks (GAN) is an increasingly more common practice for the architectural design process, being capable of automating building design tasks and, thus, reducing costs [206]. Nevertheless, according to Parente et al. [206], these are mainly used by researchers and experts, not building design professionals.

Despite the substantial contribution of programming in general, BEM, sensors, and LCA constitute the most common practices identified in the literature. The combination of these topics has already been discussed in Section 3.3. Nonetheless, its importance for modern modular construction is worth noting, as digitalisation and sustainability are key factors. Moreover, from a broad perspective, IoT (Internet of Things) is the most used digital technology, encompassing sensors, RFID tags, and worker's wearable devices. In fact, there has been a significant increase on using IoT in the building prefabrication industry, in addition to the growth of artificial intelligence (AI) methods [36]. Due to the significant increase in IoT adoption on modular construction, it was possible to find a considerable number of publications addressing monitoring strategies, either in the Digital Twin direction or through smart homes.

It is noteworthy that, despite the growing use of machine learning and AI, few articles were identified focusing on applying these techniques to optimise the creation of sustainable and energy-efficient modular buildings. Garcia et al. [96] explored strategies for enhancing energy efficiency using data mining tools, while Zhou and Xue [119] implemented a symmetric skeleton grammar-based multi-objective optimisation of passive design for energy savings and daylight autonomy. These are the only instances that incorporated energy parameters directly into the design process rather than merely assessing them afterward through BEM analysis. However, none of these studies based their optimisation process on LCA parameters. Some authors managed to develop their models using visual programming and subsequently evaluating their LCA [104,135], but they did not integrate sustainability parameters into the code to optimise the design process prior to that evaluation, thus not benefitting from AI-based tools for this purpose. These findings support the observations of Ikudayisi et al. [14], who noted a lack of AI applications to evaluate the sustainability performance of modular buildings. Additionally, in this context, AI-driven optimisation design approaches could be further enhanced to incorporate, within a unified workflow, not only sustainable and architectural options but also other factors, such as structural design [36].

4.2. Sustainable Industrial Manufacturing

Modular construction, as an integral part of the prefabrication industry, benefits from using high-precision technologies from manufacturing applied in the Construction 4.0 context, namely 3D printers, CNC (Computer Numerical Control) machines, among others, thus allowing for the optimisation of financial, material and time resources [13]. Based on the articles assessed during the review, it is possible to conclude that there is an interest in streamlining the off-site prefabrication process, hence the adoption of technologies such as 3D printing [28,84,97,124], CNC machines [138,141], and also off-site robots [124,129].

Most industrial production sectors already deploy robots regularly, such as the automotive and electrical component industries; however, this is still far from reality in the construction industry, as it is still viewed with scepticism [1]. Robots in the AEC sector complement manual labour and reduce human efforts due to their high precision and consistency, achieving efficient and flexible production [38]. Jiang et al. [124] presented one of the Digital Twins identified during this literature review, simulating on a small scale the on-site construction process of prefabricated modules using a robotic arm. Indeed, according to the recent literature, this type of robot is, by far (79.5%), the most common for modular construction purposes [38]. Also, on Oorschot and Asselbergs [129], the sustainable and customisable modular solution “Uuthuuske” is produced with the aid of off-site robots, although no information is provided regarding which type had been implemented.

Digital models are the basis of automated fabrication with CNC machines [1,13], including BIM models that are then converted into proper formats with the specifications for the equipment to produce and cut the materials [13]. Note that this method is advantageous to produce wood and metal elements [1]. Therefore, the use of CNC machines guarantees high precision and tight tolerance quality control on the finalised product [13], although some critics argue that this leads to excessive construction standardisation, thus lacking individuality [207]. For the cases assessed during this review, Wasim and Oliveira [141] intended to optimise the DfMA-based structural design of a modular bathroom pod using CNC machines. These machines have also been adopted to streamline the DfMA-based modular digital fabrication process for emergency temporary usage in catastrophe scenarios [138]. Furthermore, it should be noted that digital fabrication with CNC machines and 3D printing is starting to be adopted as a low-cost, fast, and customisable solution for humanitarian purposes [208].

Although 3D printing, also known as additive manufacturing, has been applied in different fields (e.g., arts, medicine, automotive, and aerospace industry) [209,210], it is considered to be an emerging technology under the Construction 4.0 scope [8]. 3D printing can produce complex shapes with high precision, thus providing high design flexibility [13,211]. This process relies on digital design to create physical objects by adding material layer by layer [8]. Hence, it is important to connect BIM with 3D printing [212]. While it was initially used to create complex designs of lower scales, 3D printing has evolved to produce large-scale volumes, which can be implemented in the construction industry too [209], including for bathrooms [213] and cultural heritage purposes [214,215]. 3D printing offers lower costs compared to traditional approaches, time savings, and improved workers' safety as printers can replace them on dangerous tasks. It is also an environmentally friendly construction process with low energy usage, capable of reducing material consumption and wastes, and capable of generating limited carbon emissions [13,209–211,216]. Even though at the end of a 3D-printed building lifecycle, it is not possible to disassemble its components, materials may be able to be recycled, depending on which were used [13]. Sustainable material options have been studied to be used as an alternative binder to cement, such as CDW, natural fibres (e.g., rise husk ash, sugarcane bagasse ash, hemp, bamboo fibres), recycled aggregates, earth, among others [13,84,209,216]. Using these alternatives makes it possible to reduce the carbon footprint of this process, thus reducing the construction's environmental impact and increasing the sustainability of the built environment [216]. In this review, only four articles implemented 3D printing in their workflow. He et al. [28] and García-Alvarado et al. [97] opted to use cement to 3D print buildings based on parametric design, while Zhang et al. [84] prioritised traditional Moroccan rudimentary construction materials, thus 3D printing compressed earth blocks applied on vernacular Moroccan architecture. It is worth noting that earth was also considered a suitable solution, as it is locally sourced, low-cost, thermally efficient, and sustainable. Finally, Jiang et al. [124], the authors of one of the studies that present a Digital Twin, also used 3D printing techniques for the small-scale modules that emulate prefabricated modules. These are then placed with the assistance of a robotic arm.

4.3. Sustainable Solutions Towards Environmentally Friendly Modular Construction

Regarding building construction solutions, most of the case studies are built with wooden panels, with some opting for metal or precast concrete. Steel is the preferred material for framing. In addition, mineral-based wools have been identified as the most common material for thermal insulation, as well as synthetic-origin solutions (particularly PUR). As already discussed, there are multiple parameters to consider when choosing insulation materials. Regarding thermal conductivity, all the materials selected for the case studies have similar values [170,171]. From an environmentally friendly point of view, synthetic materials are not good options compared to rock wool and, especially, cork [171–174]. Additionally, this natural and renewable material is considered an efficient and recyclable option [173,174]. It is the only building insulation material in the market with a negative carbon footprint [174]. Interestingly, the case study buildings that opted to use cork as the insulation material are among those that consumed less energy [135,136]. However, despite its environmental benefits, cork is not a good option from an economic perspective [173]. In addition to the aforementioned examples, there were two publications that opted to use uncommon insulation materials, which presented a favourable thermal behaviour, particularly crop waste (straw in this case) [101] and recycled PET bottles [140]. Both solutions were stated as being environmentally friendly options.

Six publications mentioned that they used recycled materials on their buildings. Savvides et al. [4] implemented recycled elements for furniture and exterior cladding finishes, while two authors opted to use CDW to produce sustainable concrete [129] and for the foundation blocks of a self-sufficient building [101]. In addition, blast furnace ash, a byproduct of steel production, was also applied to the soil to be used as anti-freeze soil padding [101]. As already mentioned, two publications opted to implement reused or recycled insulation materials on their buildings: Shao et al. [101] used crop waste material (straw) for the wall's thermal insulation, while Moga et al. [140] recycled PET (polyethylene terephthalate) bottles and, with its polyester fibres, managed to implement recycled PET thermal wadding as a sustainable insulation solution for both walls, floor, and roof. Meanwhile, O'Grady et al. [142] reused 58% of the materials, particularly steel (including structural) and wood, in addition to multiple recycled materials (e.g., balcony tiles made of recycled rubber and plastic waste or acoustic panels made of recycled PET plastic). Apart from this example, the other cases that adopted material reuse strategies are exclusively related to converting maritime containers into housing units [100,115,123,136]. In addition, Tong et al. [115] reported that after the end of the 2022 Winter Olympic and Paralympic Games, the temporary containers used during the event were recycled and transformed into convenience stores, hotel rooms, and so on, on a clear circular construction mindset.

Based on the previous information, it is possible to conclude that there is great potential to apply a "Cradle to Cradle" approach since prefabricated modules can be dismounted and then recycled in other manufacturing processes. Starting by analysing the concrete, it was possible to note its relevance, particularly for high-rise construction. As such, from a sustainable construction standpoint, it is worth mentioning that concrete can come from recycled materials or material waste (e.g., CDW) [13], as already verified in two of the aforementioned examples [101,129]. Nonetheless, concrete manufacturing is a process with high energy usage and CO_2 emissions levels, while wooden manufacturing is a low-energy process with limited carbon emissions [4,13]. Coincidently, the case studies that used wooden panels on their buildings have lower global warming potential and energy use [4,95,104,115,132,135,136]. Hence, it is essential to adopt sustainable building materials to reduce the impacts on the environment significantly.

Three solutions are highlighted regarding the building's framing: steel, reinforced concrete, and wood. As was the case for concrete, steel production is a process with high levels of energy usage and CO_2 emissions [4,13]. Thus, wooden framing is the best option in terms of sustainability, particularly since wood is a carbon-negative material [207]. As was the case for wooden panels, wooden-framing modular buildings presented low global warming potential and low energy use [135,136]. In order to reduce the impacts of using materials considered to be less sustainable, some options must be taken into account, for instance, the use of local products to reduce transport distances (and therefore reducing embodied carbon emissions), the use of products with lower embodied carbon by analysing data from EPDs (environmental product declarations), and the reuse of building components [196]. Indeed, a circular economy may lead to interesting results from unconventional but feasible ideas. An example is the reuse of bicycle frames to produce the structural framing of modular building units [217]. Also, it must be noted that reducing the embodied carbon emissions of a building is a way to achieve an nZEB standard [103].

Many articles do not address active and passive strategies; consequently, much information cannot be retrieved. Despite this limitation, it was possible to note the preference for HVAC systems and solar energy-related options (in particular, photovoltaics and solar thermal systems) for active solutions. Regarding the passive solutions that were possible to assess, the preference was given to thermal insulation, direct solar gains, natural ventilation, and natural lighting, in addition to shading systems and building airtightness.

Some authors aimed to design their buildings according to the climate where they were to be located [64,85,115,118,123,135], on a concept known as bioclimatic architecture, which is of utmost importance for the optimisation of energy efficiency, thermal comfort, and sustainability, by promoting adapted solutions to the local climate [218–221].

No article explored automated solutions for solar radiation control, such as thermochromic windows or adaptive solar façades, which respond automatically according to the incident solar radiation. Instead, automation systems were used from a smart home perspective [4,94,118,123,131], such as turning on/off the mechanical ventilation based on temperature recordings. A similar logic is followed to turn on/off the radiant underfloor heating system in a prototype through interior temperature recordings [125,126]. Finally, one study [118] implemented manual remote controls to regulate the angle of their shading systems. Nonetheless, this approach differs from the one adopted for adaptive solar façades, as the process is not automated.

Five articles described creating self-sufficient modular buildings [4,101,118,123,140] by combining optimal active and passive building solutions to renewable energy resources, with prevalence for solar energy but with some cases of geothermal and wind energy. Considering the worldwide environmental issues (e.g., deforestation) and as fossil fuel energy sources are still the primary source of energy in the world, it is crucial to promote renewable energy sources and develop prefabricated off-grid housing solutions [222]. Moreover, some of these authors opted to use recycled materials in their studies [4,101,140], which prevents the waste of potentially useful materials and minimises the likelihood of being sent to incineration or landfill sites. As such, reducing reliance on such disposal methods contributes to decreasing air and water pollution, thereby protecting the environment [101].

Off-grid energy systems are gaining popularity as independent energy sources for individual households or smaller communities, particularly in remote areas where extending the main electrical grid is impractical or costly [223]. Historically, these off-grid systems have been relying on generators powered by fossil fuels, such as diesel [223–226]; however, these are gradually being replaced or hybridised with renewable energy sources [226]. Some authors suggest that, ideally, off-grid solutions should be applied to a whole village or community instead of focusing on singular households [224,225,227], contrary to all the off-grid modular buildings featured in this literature review. Nonetheless, the implementation of such systems may not be feasible in numerous contexts, particularly in apartment buildings, where the limited roof area restricts energy generation capabilities. Consequently, such installations are unlikely to meet the energy demands of all households within these structures. Adding to this, the current energy storage prices make it an unattractive option for most homeowners. Advancements in photovoltaic technology to capture diffuse irradiation could present solutions for such cases, paired with the reduction in energy storage costs [228].

5. Conclusions and Future Works

New technologies have been revolutionising the construction industry following a concept known as Construction 4.0 [8]. Modular construction adoption has been rising recently due to investments in the sector disrupted by the COVID-19 pandemic [82]. The same also applies to these new technologies [81]. Therefore, this review provides an overview of the connection between these, with particular attention to BIM and Digital Twin integration. Apart from that, building construction solutions, including their respective thermal-related properties, in addition to active and passive systems, are also assessed. This is of particular importance to understanding customisation options for different climate zones.

Besides the innovative digital technologies and building physics perspectives, sustainability and environmental protection are among the main pillars of this review, considering the European Union's strive to be climate-neutral by 2050 [29–32]. Hence, it is important to aim for a nearly-Zero Energy Building (nZEB) and, particularly, for off-grid modular housing. These self-sufficient modular buildings should follow a DfMA philosophy to take advantage of the benefits of this approach from an environmental and a social–economic point of view while promoting building circularity, ideally from a "Cradle-to-Cradle" perspective. Moreover, further research must focus on ensuring the development of Zero-Emission Buildings (ZEBs) in order to further enhance the decarbonisation of the built environment as highlighted by the European Union's Energy Performance Building Directive (EPBD) [32].

In this review, most papers focus on BIM uses; however, there is a clear interest in integrating real-time data to connect modular buildings to their corresponding digital model. In fact, IoT has been identified as the most used digital technology under this review's scope. Indeed, with the rise of IoT adoption for modular construction, it was possible to find a considerable number of publications addressing monitoring strategies, whether related to Digital Twin technology or smart home solutions. Seven Digital Twins (where information flows in a bidirectional way) have been identified in this literature review [107–110,112,120,124], all of them for modular construction projects in Hong Kong. In addition, smart homes proved to be a great tool for automated and personalised building control. Apart from IoT applications, multiple examples have been found regarding BEM and LCA studies, which reflect the increasing interest in climate-friendly housing. Moreover, automated design tools such as generative and parametric design have been identified as one of the main applications in the context of digital-oriented modular construction. In turn, machine learning and AI tools have only been briefly addressed. As detailed in Section 4.1, both technologies have the potential to optimise the creation of sustainable and energy-efficient modular buildings. However, this remains a research gap that must be tackled in the future.

Most of the case studies collected are in Asia, which focus on high-rise construction. Some areas are underrepresented, such as Africa, the Middle East, Latin America, and the Caribbean, as well as Oceania and Antarctica. Generally, residential buildings are the most common, while most of the papers' focal point is on the design stage, where digital technologies can streamline the process [25–28]. Moreover, while the DfMA philosophy in modular construction has prompted some research on material circularity, namely through LCA tools, none explored implementing digital applications in a real-world modular deconstruction scenario. Therefore, this has been identified as a research gap.

In terms of building construction solutions, most of the case studies are built with wooden panels, with some opting for metal or precast concrete. Steel has been the preferable material for structural framing. In addition, multiple insulation materials have been identified, mostly of mineral and synthetic origins. Apart from HVAC systems, solar energy-related active systems are the most used (particularly photovoltaic panels and solar thermal systems), while multiple passive systems are adopted to reduce heating and cooling loads. Given that the primary goal of sustainable modular buildings is to have low energy consumption during the operational phase [19,39], it is worth noting that only a few papers managed to reach nZEB standards or self-sufficiency. Despite this, there is a clear focus on renewable energy sources (notably solar energy), which contributes to this goal [19,39]. Additionally, some articles already cover recycled and reused materials, although material circularity still holds unfulfilled potential concerning sustainable and carbon-neutral modular construction. Moreover, future research could investigate the potential of having entire sustainable off-grid communities based on modular construction methods. This topic could also potentially extend to the contributions of digital tools, such as IoT, smart homes, and Digital Twins, to create smart grids in this context.

The most fundamental finding of the study is that integrating modular construction with digital technologies improves design processes, reduces error rates, and increases collaboration between stakeholders. In addition, this digital integration plays a critical role in achieving sustainability goals. For instance, real-time data integration strengthens the connection between modular buildings and digital models, contributing to a reduction in environmental impacts by optimising the regulation of the units' systems through analytics [229]. These findings highlight the potential of digitalisation in modular construction to enhance efficiency and ensure environmental sustainability within the AEC sector.

Moreover, considering that this literature review is part of the early developments of a multidisciplinary project involving both the industry and academia, it is relevant to note that the least explored residential applications are student and senior residences, followed by hotels. Therefore, these must be among the future priorities to address. In addition, no full-scale automated Digital Twin was found in the scope of digital-oriented modular construction. However, given the developments of the aforementioned Hongkonger studies, it is likely that this gap could be filled soon, although they may not be aiming at sustainability goals. It is also noteworthy that, ideally, these Digital Twins should be based on an openBIM methodology, considering that openBIM can enhance coordination and collaboration by facilitating the interoperability of BIM models among different stakeholders [25,27,28].

Future works will focus on implementing a BIM-based Digital Twin for a full-scale modular building that adopts a passive building design allied to renewable energy solutions and a circular construction ideology towards self-sufficiency and carbon neutrality. To achieve this, a multidisciplinary team will have to work together to conceive this goal while aiming to reproduce a scalable modular building capable of adapting to a multitude of climate zones and customisation requirements.

This review provides valuable information on the current state of the art regarding modular construction; however, this research only collected papers integrating this prefabrication method with digital technologies. Thus, these data are purposely biased towards this interconnection. Therefore, this analysis does not intend to assess the whole spectrum of modular construction and its practices other than the ones referred to in this article. Further investigation must be performed if a complete analysis of modular construction practices is intended. Moreover, this review does not address structural options for modular construction (e.g., shear walls or load-bearing walls) except for the material, nor acoustic or economic analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15050765/s1, Table S1.1: Article distribution by climate zone and building material information; Table S1.2: Thermal insulation characteristics by the case studies' construction elements; Table S2: Active and passive building solutions; Table S3: Environmental sustainability indicators, by climate zone. References [230,231] are cited in the supplementary materials.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
BEM	Building Energy Modelling
BIM	Building Information Modelling
BIPV	Building-Integrated Photovoltaic
CDW	Construction and Demolition Waste
CNC	Computer Numerical Control
DfMA	Design for Manufacture and Assembly
EPS	Expanded Polystyrene
FEM	Finite Element Modelling
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
IoT	Internet of Things
LCA	Life Cycle Assessment
nZEB	nearly-Zero Energy Buildings
O&M	Operations and Maintenance
PCM	Phase Change Material
PET	Polyethylene terephthalate
PIR	Polyisocyanurate
PUR	Polyurethane
PV/T	Photovoltaic and Thermal
PVC	Polyvinyl chloride
RFID	Radio-Frequency Identification
U	Thermal transmittance coefficient
VR	Virtual Reality
XPS	Extruded Polystyrene

Including the following Köppen–Geiger climate zones:

Af	tropical rainforest
Aw	tropical savanna
BSh	hot arid steppes

BSk	cold arid steppes
BWh	hot desert climate
Csa	hot summer Mediterranean climate
Csb	warm summer Mediterranean climate
Cwa	dry winter humid subtropical climate
Cwb	subtropical highland climate (temperate oceanic climate with dry winters)
Cfa	humid subtropical climate
Cfb	oceanic climate
Dwa	dry winter humid subtropical climate
Dfa	hot summer humid continental climate
Dfb	warm summer humid continental climate

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