smart cities

MDPI

Review

Climate Change Mitigation through Modular Construction

Zeerak Waryam Sajid [1], Fahim Ullah [2,*], Siddra Qayyum [2,3] and Rehan Masood [4,*]

[1] NUST Institute of Civil Engineering (NICE), National University of Sciences and Technology, H-12, Islamabad 44000, Pakistan; zsajid.bece19nice@student.nust.edu.pk
[2] School of Surveying and Built Environment, University of Southern Queensland, Toowoomba, QLD 4300, Australia; siddra.qayyum@unisq.edu.au
[3] Faculty of Society & Design, Bond University, Gold Coast, QLD 4229, Australia
[4] Department of Civil and Environmental Engineering, The University of Auckland, Auckland 1023, New Zealand
* Correspondence: fahim.ullah@unisq.edu.au (F.U.); rmas769@aucklanduni.ac.nz (R.M.)

Abstract: Modular construction (MC) is a promising concept with the potential to revolutionize the construction industry (CI). The sustainability aspects of MC, among its other encouraging facets, have garnered escalated interest and acclaim among the research community, especially in the context of climate change (CC) mitigation efforts. Despite numerous scholarly studies contributing to the understanding of MC, a holistic review of the prevailing literature that systematically documents the impact of utilizing MC on CC mitigation remains scarce. The study conducts a systematic literature review (SLR) of the pertinent literature retrieved from the Scopus repository to explore the relationship between MC and CC mitigation. Employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, the SLR was conducted on 31 shortlisted articles published between 2010 and 2023. The findings of the study reveal that MC can mitigate the climate crisis by reducing GHG emissions, curtailing resource intensiveness by enabling a circular economy (CE), fomenting energy efficiency, and fostering resourceful land use and management in the CI. A conceptual framework based on the findings of the previous literature is proposed in this study, which outlines several strategies for CC mitigation that can be implemented by the adoption of MC in the CI. The current study is a humble effort to review various offerings of MC to help mitigate CC in the era of striving for global sustainability. For industry practitioners and policymakers, this study highlights the viability of leveraging MC for CC mitigation, aiming to inspire better decision making for sustainable development in the CI. Similarly, for researchers, it presents MC as a potential tool for CC mitigation that can be further explored in terms of its associated factors, and focused frameworks can be developed.

Keywords: climate change; climate mitigation; construction industry; literature review; modular construction

Citation: Sajid, Z.W.; Ullah, F.; Qayyum, S.; Masood, R. Climate Change Mitigation through Modular Construction. *Smart Cities* **2024**, *7*, 566–596. https://doi.org/10.3390/smartcities7010023

Academic Editors: João Quesado Delgado, Ricardo Forgiarini Rupp and Pierluigi Siano

Received: 7 January 2024
Revised: 1 February 2024
Accepted: 5 February 2024
Published: 8 February 2024

1. Introduction

Climate change (CC) is a serious threat faced by humanity in the modern age. Taking place at a staggering rate, CC is accountable for the frequent occurrence of natural disasters and extreme weather events witnessed nowadays. Events like the Black Summer fires in Australia, which caused extensive damage to infrastructure and the natural landscape, have been linked to CC [1]. Extreme rainfalls caused by CC during the monsoon of 2022 resulted in a devastating flood that adversely affected one-third of Pakistan [2]. CC's catastrophic tendencies, like frequent floods, cyclones, wildfires, and droughts, present a grave threat to communities and infrastructure around the globe [3,4]. Therefore, developing CC resilience lies at the heart of modern-day research owing to its profound significance and alarming implications. In the wake of these circumstances, researchers and practitioners, especially within the built environment, have taken up CC mitigation as an urgent priority since the construction industry (CI) has been declared a major contributor to CC [5]. "Build back better" is one such recent concept that highlights the importance of resilience against climate change and signifies the role of construction [6].

For context, the CI is attributed to 36% of total greenhouse gas (GHG) emissions measured across all industries annually [7]. The CI generates large amounts of construction and demolition waste (CDW), accounting for 35% of landfilling around the globe [8]. The CI is also a generous consumer of raw materials since 40% of raw stone, gravel, and sand are consumed in construction annually [9]. In addition, the construction and operation of buildings are responsible for 39% of global energy consumption, surpassing any other individual sector [10]. Moreover, the CI is expected to grow to accommodate the world's increasing population; if left unchecked, it will continue instigating CC extensively through its hazardous environmental implications. To cope with the detrimental effects of CI activities inciting CC, industry professionals and researchers have come forward with several concepts, measures, and techniques that could help mitigate CC. These include using sustainable materials like geopolymers, carbon accounting, energy-efficient design and construction, lean construction, and circular economy (CE), to name a few [11]. In this perspective, one of the most promising concepts is that of modular construction (MC) owing to its sustainability considerations and environmental benefits [12]. It is essential to adapt the CE approach to the "build back better" strategy for modular buildings. Such adaptation will help reduce the risk of future catastrophes and the impacts on climate and natural resources. In this context, setting up clear guidelines for CE adoption is pivotal in helping the industry define and oversee its efforts towards these objectives, which are currently lacking [13].

MC, or volumetric or off-site construction, is a process that helps construct a building off-site, under controlled plant conditions, using the same materials and designed to the same codes and standards as conventionally built facilities but in about half the time [14]. Modular integrated construction (MiC) is the preferred form of MC used for tackling natural and man-made disasters [10]. In MC, buildings are produced in "modules" and, when put together on site, reflect the identical design intent and specifications of the most sophisticated traditionally built facility without compromise [15]. In MC, building components are fabricated in a remote factory or location and transported to the construction site for installation, unlike conventional or on-site construction, whereby entire structures are built from the ground up on the project site. Overall, MC enables up to 75% of buildings to be constructed off-site in a controlled environment, which fosters significant environmental benefits as opposed to on-site construction [15]. These benefits include substantially reducing construction waste, resource optimization, lowering GHG emissions, reducing noise, and minimizing environmental disruptions [12]. Improved indoor air quality, lower energy consumption, and higher reusability upon decommissioning of buildings are also appreciable aspects of MC's ecology [16]. These environmental benefits of MC over traditional methods imply that MC is a useful tool for fostering sustainable development in the CI. Apart from its sustainable and green construction prospects, MC has several added merits over on-site construction, which are tabulated in Table 1.

Table 1. Differentiating aspects of MC and on-site construction.

Construction Method	Cost Saving	Fast-Tracking	Engaging Local Workforce	Quality Control	Fewer Size Limitations	Reusability	Design Flexibility	Higher Salvage Value	Energy Conservation	Resource Optimization	References
Modular	✓	✓	x	✓	x	✓	✓	✓	✓	✓	[17–22]
Traditional	x	x	✓	x	✓	x	x	x	x	x	

MC can reduce project time by 50% through better planning and execution of its work packages [17]. The construction cost of MC projects is also reduced by 25% compared to conventional construction projects of the same scale [18]. MC also offers improved quality control over projects due to the factory setting and standardized processes [19]. Against its significance, numerous comprehensive review studies have been conducted to consolidate and expand upon MC's current research advancements and industrial implementations. The structural performance and durability of modular buildings have been documented in multiple studies, each pointing out its potential to enable secure and resilient housing [23].

Despite numerous advantages, MC is not colossal and has certain disadvantages. It has received a fair share of criticism. For example, Kamali et al. [24] criticized the inconsistent environmental performance of MC and argued that MC is not the absolute option for environmentally friendly construction. Other concerns include complicated transportation of the modules, complex and demanding coordination of production and construction, lack of acceptance of this technology by industry professionals, and low public demand [25]. Infiltration between the building components is another concern [26]. While the discussed issues are acknowledged, these are addressable, and various mechanisms have been presented to cope with them. Further, in the case of MC, the benefits far outweigh the disadvantages; hence, many studies present it as a preferred construction method.

Comprehensive reviews have compiled numerous construction materials that are used in the preparation of prefabricated modules, such as wood, light gauge steel, and structural insulated panels, as opposed to traditional construction, which mainly relies on in situ concrete and heavy steel reinforcements for building components [27]. Similarly, regarding various management philosophies, Arashpour discussed employable management philosophies in MC projects since predictive project delivery methods, predominantly used in traditional construction, are not largely compatible with MC projects [28]. Risks associated with MC-based projects have also been reviewed to provide critical insights into the potential pitfalls of such projects for their effective planning and execution [29]. Detailed reviews addressing the integration of MC with digital technologies such as BIM, blockchain, and IoT have documented the potential benefits of the coalition between MC and such technologies for automating MC processes [30,31]. Other notable works have shed light on barriers impeding the widespread adoption and potential enablers of MC in the CI [32,33].

Despite the extensive scrutiny of MC and its various aspects, no study has holistically reviewed and documented the potential utility of MC for mitigating CC, reflecting a research gap. To date, little effort has been made to comprehend the intricacies of MC and how it can help to mitigate CC. Though some studies address the individual eco-friendly aspects of MC, such as its waste minimization and resource efficiency, a detailed review that comprehensively presents the merits of MC in the context of CC mitigation is missing, presenting a research gap [34]. To address this research gap, the current study delves into the existing literature to comprehend and illustrate the feasibility of using MC to enhance CC mitigation. Two research questions addressed by the current study, prevailing due to the literature gap, are as follows:

1. What are the implications of adopting MC on CC mitigation in the CI?
2. What strategies pertinent to MC could be implemented for mitigating CC?

The current study is a novel approach to reviewing the potential benefits and implications of MC adoption in the CI on CC. Unlike existing studies, it directly addresses the holistic impact of MC on CC instead of presenting a fragmented commentary on the individual environmental impacts of MC, which is often not linked to the larger implications on the built environment [34,35]. In addition, the current study outlines specific CC mitigation strategies that can be implemented by adopting MC, which previous studies have not reviewed. While previous studies have reported the environmental benefits and sustainability of MC, research gaps have prevailed regarding the understanding of links between CC and MC and its prospective role in fostering a climate-friendly construction, which the current study aims to address [36].

Accordingly, a systematic literature review (SLR) is conducted in this study to comprehensively identify, describe, and document the benefits, impacts, and strategies to implement MC for mitigating CC based on the available literature. The existing body of knowledge points out that the CI contributes to CC primarily through excessive GHG emissions, resource intensiveness, waste generation, inordinate energy consumption, and disruptive land use [7,37]. Therefore, the feasibility of employing MC for CC mitigation is explored through the lens of these contributing factors, and the study's findings pertaining to the mentioned parameters are documented. Detailed insights concerning the utility of MC in the backdrop of CC are reported, and an in-depth discourse is provided on the implications of the study's findings. Ultimately, a conceptual framework is formulated by drawing upon the findings of the prevailing literature. The framework is aimed to delineate a viable pathway for mitigating CC in the CI. The framework strategically outlines strategies pertinent to MC, which can foster CC mitigation upon their prospective implementation.

The current study aids policymakers and industrial stakeholders by highlighting the viability of MC to foster sustainability in the CI. It is aimed to direct future research endeavors toward exploring other facets of MC, which can facilitate its holistic adoption in the CI for addressing CC. It further provides insights into the potential of advancing sustainable development by leveraging MC. The remaining study is organized as follows: Section 2 discusses the methodology for conducting the current study. Section 3 presents the study's findings obtained through an in-depth review of the available literature. Section 4 dissects the findings of the study and engages in a detailed discussion regarding the results. Finally, Section 5 concludes the study, mentions its limitations, and provides recommendations for future studies.

2. Methodology

The research methodology adopted to conduct this study is outlined in Figure 1.

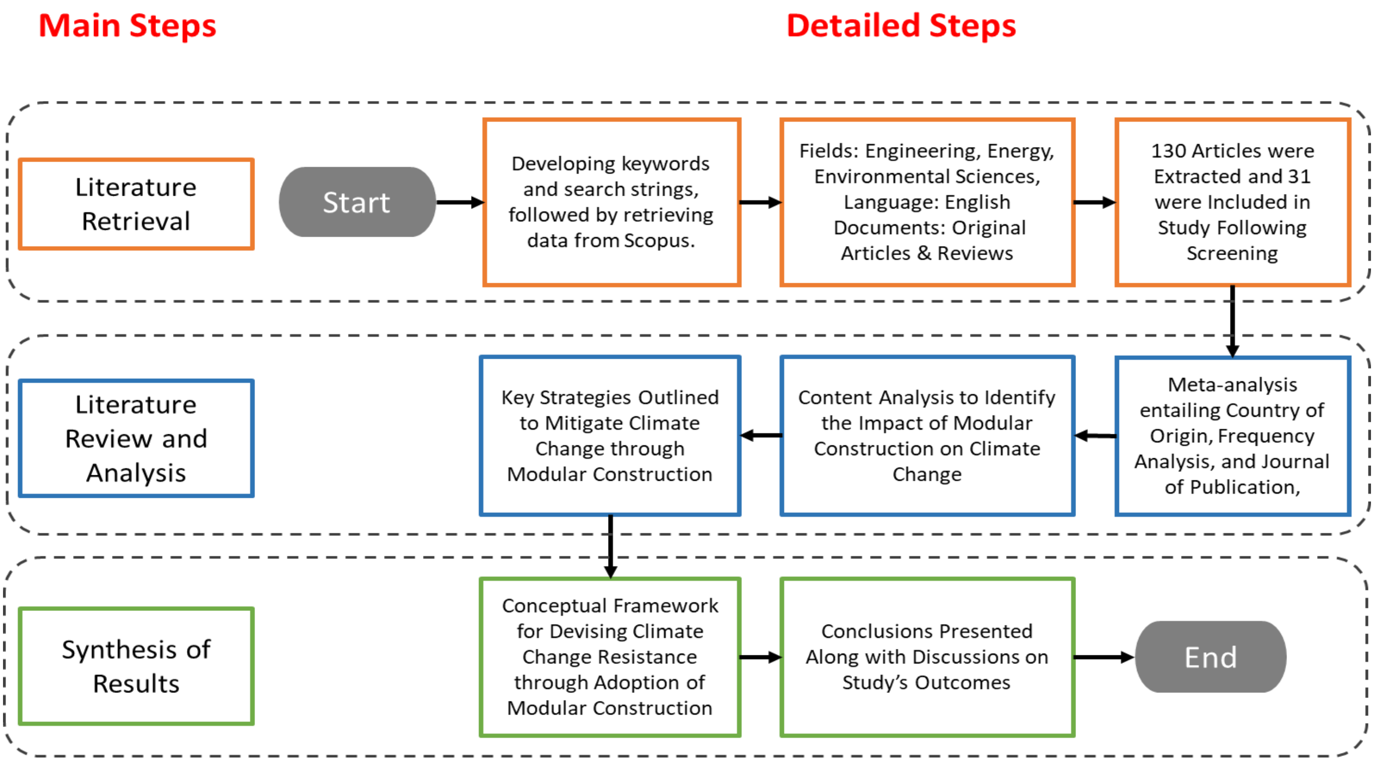

Figure 1. Methodology flowchart.

In the first step of the review process, the literature was retrieved from the Scopus repository using a detailed search string based on predefined keywords, which entailed different combinations of MC, prefabrication, CC, and the CI, as listed in Section 2.2 of this study. The search timeline selected for the study spanned from 2010 to 2023 to retrieve recent articles. From the 130 retrieved articles, 31 pertinent studies were chosen based on the predefined criteria. These criteria involved selecting articles published in English and limiting the articles to engineering, energy, and environmental sciences fields and the article type to "articles" and "review papers". Studies from sources other than scientific journal articles were excluded. Metadata regarding the shortlisted studies were extracted, and content was analyzed to bring forth insights from the literature regarding the impact of MC on CC. The effect of MC on the predominant instigators of CC in the CI, i.e., GHG emissions, resource intensiveness, excessive energy consumption, and inadequate land use, was explored and documented in the study. Finally, a conceptual framework is proposed in this study to mitigate CC and develop resilience in the CI through specific MC-related strategies.

2.1. Research Strategy

This study employed the SLR methodology to holistically gather insights from the prevailing literature regarding the impacts and implications of deploying MC for CC mitigation. The selection of the SLR approach for this study was driven by its comprehensive and systematic approach and its consistent utilization in multiple research endeavors to identify and characterize the body of knowledge regarding CC mitigation [32,38]. This study strictly adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols to validate the process of SLR. Following the PRISMA guidelines, this study followed key considerations, as outlined by Ullah et al. [39]. For conducting a holistic SLR to scrutinize the literature addressing MC in the context of CC mitigation. These considerations are as follows:

1. The review process involved the assessment of articles retrieved based on keywords from the Scopus repository. These articles were published between 2010 to 2023. The specified timeframe was chosen as a massive influx of publications addressing MC was reported during this period [34].
2. Articles incorporating the specified keywords in their title, abstract, introduction, or keywords sections met the eligibility criteria defined for this study.
3. The information source or database used for the research is the Scopus repository, accessible at https://www.scopus.com/search/form.uri?display=basic#basic (accessed on 1 December 2023).
4. The search process utilized thorough search strings, as outlined in Section 2.2 of the study.
5. The article selection process involved searching and screening articles, focusing on original articles, and reviewing papers with a rigorous peer review to ensure that validated literature backed by scientific evidence was chosen for the study. Conference papers, book chapters, and data papers were excluded from consideration because of the limited peer backing attributed to them. The selection process further narrowed the study to articles published in English and excluded studies from unrelated disciplines such as business administration, gender studies, arts, etc. It also included a qualitative analysis involving the reading of titles and abstracts. Removing duplicated articles was unnecessary as the data were extracted from a single repository.
6. Meta-analysis was conducted on the shortlisted articles using the Scopus "Analyze Results" tool. Metadata related to the chosen research theme, including the frequency of publications per year, country of origin, and publication sources, were extracted accordingly. Detailed discourse regarding the implications of the retrieved metadata has been documented in Section 3.1 of the study.
7. A thorough screening of the extracted studies was carried out to eliminate irrelevant articles. This involved reviewing the extracted studies' titles, abstracts, introductions, and conclusions. After this initial screening, content analysis of the eligible articles was performed by thoroughly reading the full texts of the shortlisted articles to identify the implications of MC on the environment and climate as documented in each study. Traditional construction was compared with MC, noting their effect on CC. Different strategies to address CC, which MC can facilitate, were identified in the shortlisted studies and recorded accordingly.
8. To mitigate the risk of bias in the study, all retrieved articles were circulated among all authors of this study. Each author independently analyzed the contents of the eligible articles. The findings of each author were then compared and subsequently

combined. Triangulating the articles among authors scrutinized the selected studies for bias before presenting the research outcomes.

9. The summary measures include identifying the advantages of MC for mitigating CC and categorizing the identified benefits into relevant groups based on their intrinsic attributes.
10. The results of the present study were cross-referenced with the existing literature to ensure validity and consistency in the prevailing research outcomes.
11. An additional analysis was conducted to propose a conceptual framework based on the enablers of CC resistance facilitated through the utilization of MC. The relevant steps are explained in the subsequent sections of this article.

2.2. Data Collection

The Scopus database was utilized to retrieve pertinent studies from the literature following PRISMA protocols, as shown in Figure 2. Other repositories, such as Web of Science, were excluded due to limited access. Google Scholar was not employed to avoid retrieving location-based results, as it utilizes Google's location-based algorithms for article retrieval [40]. Scopus is acknowledged as a state-of-the-art literature indexation and management database in construction, engineering, and management (CEM), affirming its appropriateness for this study. Further, it is free to access in most, if not all, countries; hence, replicating the results is easier compared to other limited-access repositories. The search strings, encompassing inclusions, exclusions, and limits used for the literature retrieval, are detailed below:

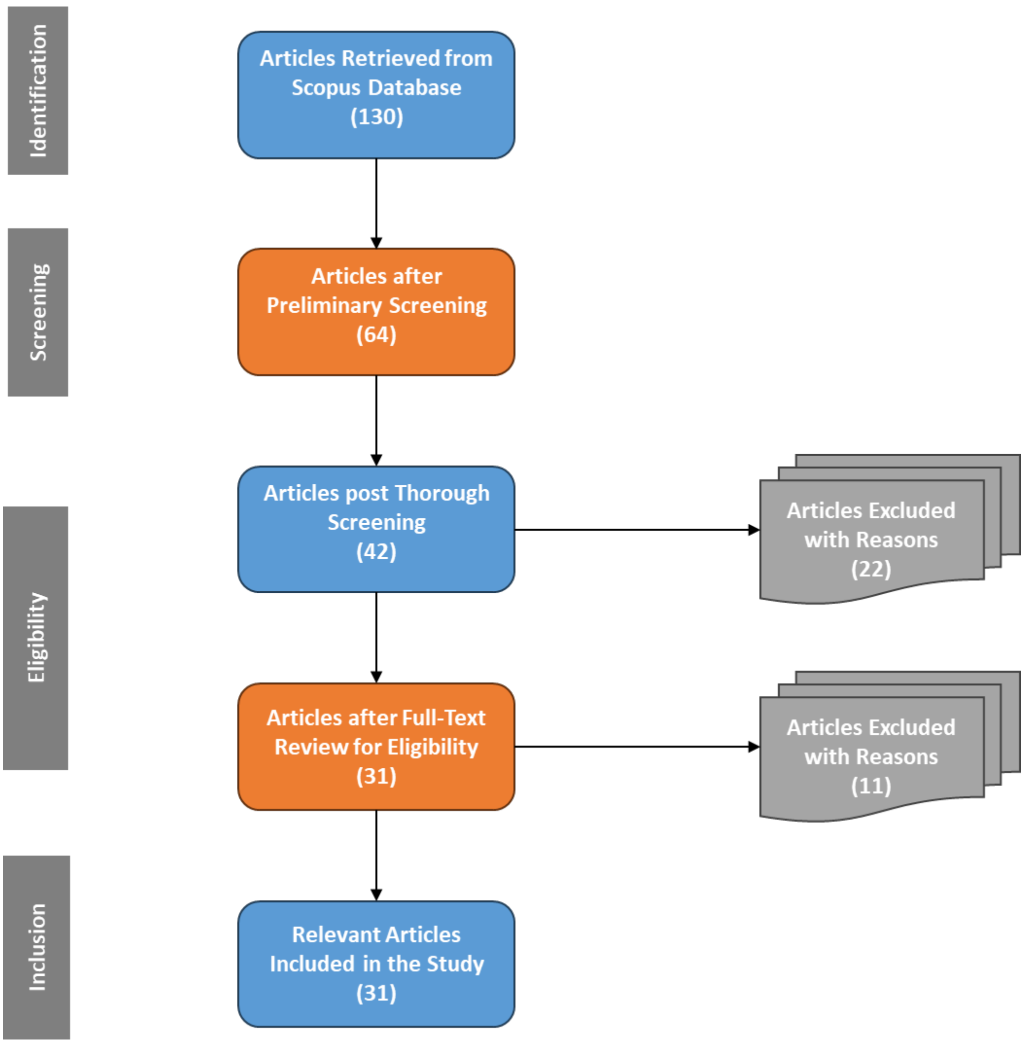

Figure 2. PRISMA flow diagram for literature review.

Inclusions: TITLE-ABS-KEY ((“Modular construction” OR “Prefabricated Construction” OR “Offsite Construction” OR “Modular Building”) AND (“Climate” OR “Climate Change”) AND (“Mitigation” OR “Resistance” OR “Resilience” OR “Management”)).

Exclusions: (SUBJAREA, “COMP”) OR (SUBJAREA, “EART”) OR (SUBJAREA, “CENG”) OR (SUBJAREA, “ECON”) OR (SUBJAREA, “SOCI”) OR (SUBJAREA, “PHYS”) OR (SUBJAREA, “CHEM”) OR (SUBJAREA, “DECI”) OR (SUBJAREA, “AGRI”) OR (SUBJAREA, “ARTS”) OR (SUBJAREA, “MEDI”) OR (SUBJAREA, “PHAR”) OR (SUBJAREA, “MATH”) OR (SUBJAREA, “BIOC”) OR (SUBJAREA, “IMMU”) OR (SUBJAREA, “VETE”) OR (SUBJAREA, “PSYC”) OR (SUBJAREA, “DENT”).

Limits: (DOCTYPE, “ar”) OR (DOCTYPE, “re”) AND (LANGUAGE, “English”) AND (SRCTYPE, “j”) AND (SUBJAREA, “ENER”) AND (SUBJAREA, “ENGI”) AND (SUBJAREA, “ENVS”).

The search string employed without applying filters presented 130 relevant articles initially. For the initial screening of studies, several constraints and filters were applied to the search string as previously listed. We also excluded studies from trade journals and gray literature by limiting the search to academic journals only, given their higher credibility due to rigorous peer review. Sixty-six studies were excluded as they did not meet the specified criteria, leaving 64 filtered articles. Subsequently, the articles underwent a thorough screening based on predefined inclusion and exclusion standards derived from previous studies of relevant nature [38]. Articles were included if they met the following criteria:

1. Exclusively address the impact of MC on climate and its role in fostering environmentally friendly construction.
2. Complete texts are accessible to readers through standard Scopus access.
3. Mention MC or prefabricated or off-site construction and climate in their abstract, title, keywords, introduction, or conclusion.

The authors thoroughly read the retrieved articles’ Abstract, Introduction, and Conclusion sections to conduct a comprehensive screening based on the prespecified criteria. Studies whose research themes did not align with MC and CC were excluded from the retrieved list. Following the screening process, 42 articles that demonstrated strong relevance to the objectives of the current study were chosen for an in-depth review. Subsequently, the complete texts of the remaining articles underwent a thorough examination for another round. After validating their eligibility and ensuring a strong alignment with the research theme, 31 studies were finally shortlisted, listed in Table A1, Appendix A.

2.3. Data Analysis

A multifaceted approach was adopted to derive insightful outcomes from the retrieved data. Firstly, the metadata about the selected articles were acquired using the “Scopus Analyze” feature of Scopus database. MS Excel Version 2401 (Build 17231.20194) was used to visualize the acquired metadata to illustrate various trends related to MC and CC. Table 2 summarizes the different analyses employed in this study and the tools used to perform them.

Table 2. Types of metadata extracted from the retrieved articles.

Sr No.	Type of Analysis	Output	Tools	
1	Frequency analysis	Number of papers published per year addressing MC and CC mitigation	Scopus Analyze	MS Excel
2	Journal source	Number of articles published by various journals pertaining to MC and its impact on CC	Scopus Analyze	MS Excel
3	Number of publications by country or region	Number of articles regarding MC and CC originating from different nations	Scopus Analyze	MS Excel

A thorough content analysis of the selected articles was conducted to contextualize the findings of the relevant literature for understanding the impact of MC on CC mitigation.

All selected articles were downloaded in portable document format (PDF) to accomplish this. Content analysis was then conducted manually by thoroughly reading the complete texts of the retrieved articles and documenting the findings of each study in an Excel sheet.

The content analysis revealed that MC could contribute to the mitigation of CC caused by the CI in four ways, i.e., reducing GHG emissions, efficient consumption of resources to curb resource depletion, hindering excessive energy consumption, and sustainable land use to conserve natural ecosystems. These parameters are the key instigators of CC, as reported by various studies. MC can help develop resistance to CC by alleviating the intensity of these aspects. A similar grouping has been used to document the effects of 3D printers on CC [41]. The content analysis also identified certain CC mitigation strategies pertinent to the CI, which can be implemented by employing MC. A conceptual framework was developed based on the identified strategies that can be implemented using MC to mitigate the global CC crisis.

3. Results

3.1. Meta-Analysis

The frequency analysis conducted in this study reveals that MC in the context of CC mitigation has gathered increased attention from the research community over recent years, as shown in Figure 3a. A steady exploration of the concerned research theme was observed from 2010 to 2018, indicating its novelty and emerging significance within the scientific and academic sphere. The literary contributions within this domain declined in 2019–2020, which can be attributed to the COVID-19 pandemic, which disrupted academic activities and research efforts globally, impeding extensive scholarly outputs during that period. A surge in scholarly works and publications addressing the impact of MC on CC was recorded in 2021. This surge in research activity can be credited to the heightened adoption of MC projects globally, which were undertaken to expedite the establishment of critical facilities like hospitals and quarantine camps to cope with the challenges raised by COVID-19 [42]. The rapid construction of the Huoshenshan and Leishenshan hospitals in China are examples of such endeavors enabled through MC [42]. The most publications were recorded in 2021, with ten literary outputs during the tenure. The mounting interest attained by MC and its potential benefits to the climate has persisted, with eight publications recorded during the year 2023. As the threats posed by the CC crisis become imminent and humanity's efforts to curtail climate disruption intensify, research addressing the role of MC in resisting CC will also increase.

Sources of publications were also analyzed to present the number of scholarly contributions made by different journals to MC and CC. By outlining the contributions of esteemed journals on MC for CC resistance, the source analysis underlines the significance of this research theme within academia and the industry. The results of the publication source analysis are displayed in Figure 3b. The results show that *Energy and Buildings* has been the most ardent contributor to the research theme, with six articles addressing MC and its impacts on CC. It is closely followed by the *Journal of Building Engineering*, which boasts five publications in the concerned domain, making it the second major source of literary contributions. Both these journals are indexed as "Q1" by the Scimago Journal & Country Rank (SJR), which substantiates the significance of the research theme and the interest of esteemed journals in addressing this area.

The number of contributions to the literature by various countries was also examined to unveil the trajectory of research regarding the concerned topic across different nations. The analysis results illustrated in Figure 3c outline the countries actively adding to the body of knowledge encompassing MC and CC. Most publications regarding the research theme can be attributed to the UK and the USA, with seven contributions each. The elevated number of publications in the UK and the USA can be attributed to an upsurge in MC within these countries, driven by the imperative to address the escalating housing demands of their expanding populations [17]. The sound research infrastructure of the mentioned countries is another appreciable factor that can be credited to increased publications. China is the third prominent contributor to scholarly publications, with five articles. The success of

MC projects observed during the COVID-19 pandemic in China has motivated researchers and industry practitioners of the nation, inciting them to explore this area actively [42].

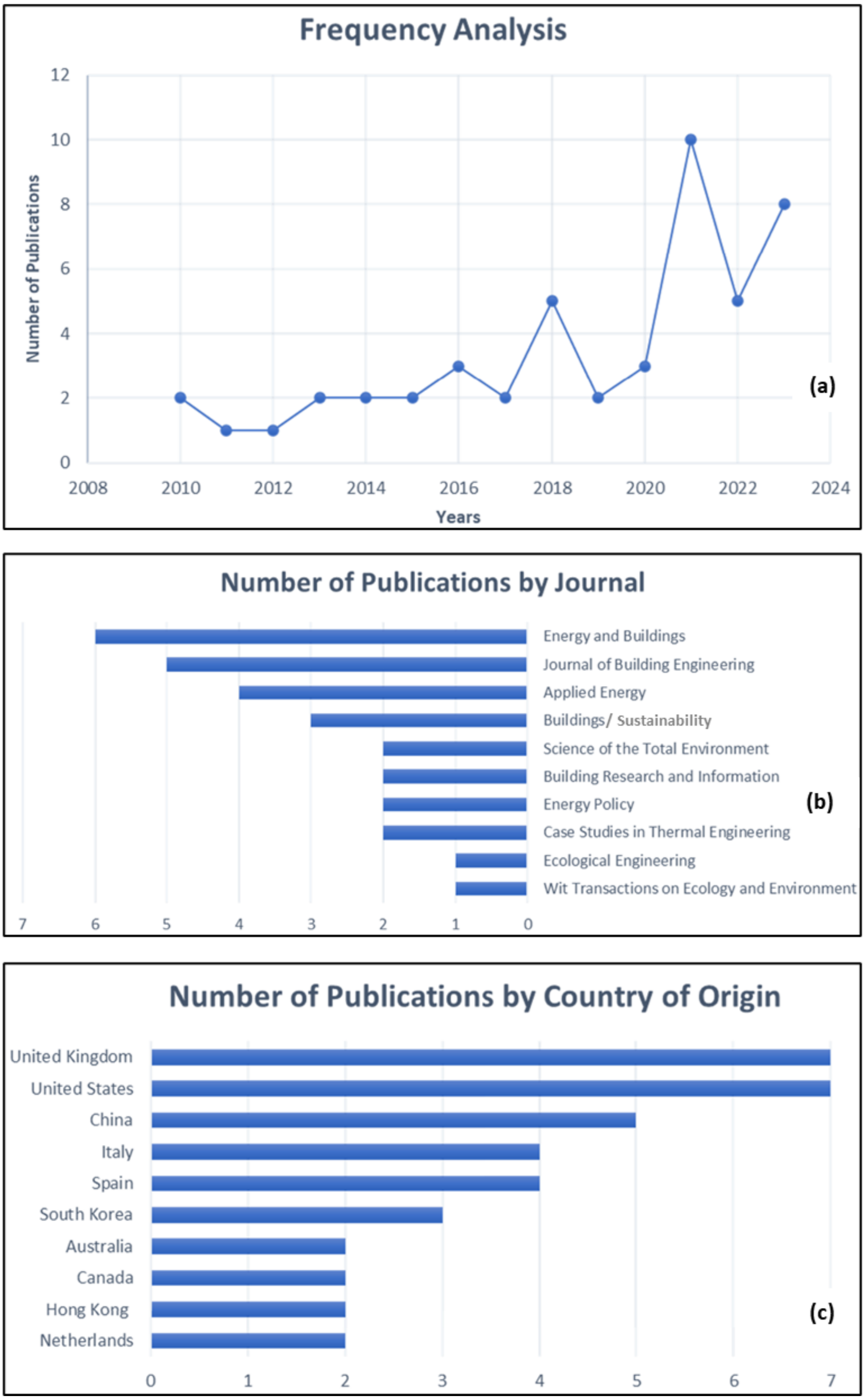

Figure 3. (**a**) Frequency analysis presenting publications per year, (**b**) top 10 journals with highest number of publications, and (**c**) number of publications per country (source: Scopus Analyze).

3.2. Content Analysis

This section entails the content analysis findings conducted on the retrieved articles to outline and document the impact of MC on CC. Manual scrutiny of the shortlisted articles reveals that MC can facilitate CC mitigation through the following:

(1) Reducing GHG emissions;
(2) Curtailing resource intensiveness by enabling a CE;
(3) Enhancing energy efficiency;
(4) Fostering resourceful land use and management.

The literature review findings pertaining to the mentioned aspects and insightful discourse on the outcomes are subsequently documented.

3.2.1. Reducing GHG Emissions

MC creates avenues for reducing GHG emissions from the CI, which is highly beneficial for CC mitigation as these emissions are widely regarded as major contributors to CC. Multiple studies have reported lower emissions for MC than traditional construction methods. MC can induce a 46.9% reduction in GHG emissions when measured against the GHG emissions of on-site construction [43]. Figure 4 compares the lifecycle GHG emissions of modular and on-site construction. Pervez [43] and Quale [34] reported a 51% and 30% reduction in MC emissions, respectively, deeming it more sustainable than on-site construction. Kamali [44], however, in their study, argued that MC can render a 12% reduction in GHG emissions compared to on-site methods, emphasizing the lower carbon footprint of MC. Other relevant findings suggest that the most significant GHG sources in construction projects include embodied emissions, emissions during the transportation of materials (modules), emissions pertinent to construction processes, and emissions during deconstruction [45].

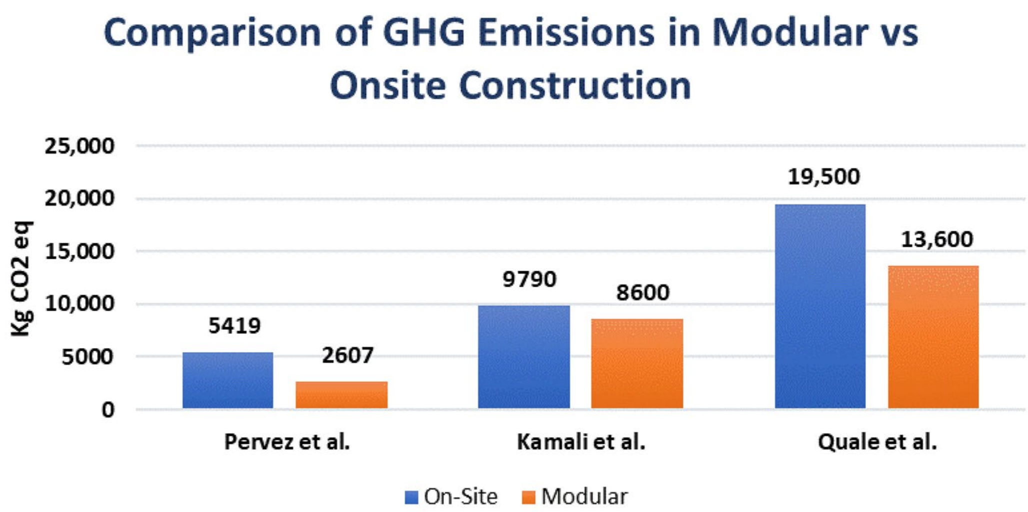

Figure 4. Comparison of lifetime GHG emissions of modular and onsite construction based on published studies [34,43,44].

According to Pervez and other literary studies, the embodied GHG emissions of building materials are responsible for the highest number of emissions in both modular and on-site construction [43,46]. However, MC achieves a substantial 51.8% reduction in embodied emissions compared to traditional construction, owing to the materials employed in it [47]. On-site construction relies heavily on using concrete as a primary building material. Around 60% of conventionally built structures are comprised of concrete, notorious for its detrimental effects on the environment, especially its exaggerated GHG emissions, which incite CC [48,49]. Research has indicated that the concrete industry accounts for 8% of total GHG emissions worldwide [50]. Therefore, excessively using concrete in on-site construction is responsible for the high embodied GHG emissions [50].

On the other hand, MC utilizes comparatively eco-friendly materials like timber, steel, plywood, and gypsum boards in its building components [46]. Even when MC utilizes concrete for building components, the proportion of concrete used in preparing modules is much lower than in traditional methods [51]. The departure of MC from Portland cement concrete as its primary building material is the major reason for lower embodied GHG emissions [52].

Table 3 compares the carbon emissions of primary building materials used in MC (steel, timber) and on-site construction (concrete). It is evident from the table that the literature attributes lower embodied GHG emissions to steel and timber as compared to concrete, accounting for the reduced embodied emissions in MC. Tavares et al. [46] reported 27% and 48% lower embodied GHG emissions for steel and timber, respectively, when measured against concrete. Hart et al. [53] documented similar findings, with steel and timber showing 18% and 47% lower GHG emissions than reinforced concrete. The lowest difference in GHG emissions between steel and concrete was reported by De Wolf [54], who argued that steel has 7% lower emissions than concrete. However, De Wolf [54] documented 48% lower GHG emissions for timber.

While it is noteworthy that MC involves higher embodied carbon emissions in metal, steel, and gypsum boards compared to on-site construction, the definitive difference lies in the impact of ready-mixed concrete (RMC) on emissions. RMC emissions in traditional construction are nearly four times higher than MC. This disparity predominantly leads to on-site construction's embodied carbon emissions being 1.6 times greater than MCs [44]. Moreover, MC is highly receptive to the use of novel and sustainable building materials such as cross-laminated timber (CLT) panels, recycled plastics, and fiber-reinforced polymers (FPR), unlike traditional construction, which creates opportunities for further reducing embodied GHG emissions in MC [55].

Table 3. Comparative analysis of embodied carbon emissions of primary building materials used in MC and onsite construction.

Author	Unit	On-Site Construction	Modular Construction		References
		Concrete	Steel	Timber	
De Wolf et al.	kg CO_2e/m^2	380	350	200	[54]
Hart et al.	kg CO_2e/m^2	228	185	119	[53]
Tavares et al.	kg CO_2e	29,000	21,000	15,000	[46]
Roni et al.	kg CO_2e	409,932	-	292,901	[56]
Alireza et al.	kg CO_2e/m^3	602	209	96	[57]

Emissions from transportation are usually reported to be on the higher end in MC. The reason is that transportation distances are increased in MC projects as raw materials are first delivered to the modular factory, where building modules are prepared, followed by hauling the fabricated modules to the construction site for assembly [58]. Conversely, on-site construction only involves transporting materials from distributors to the construction site, which are used for building different components [59]. As a result, more fuel is consumed during transportation in MC, accounting for its higher emissions. However, it is to be noted that these emissions are much lower than the embodied emissions of on-site construction materials, and the lifetime GHG emissions of MC are still lower than those of traditional construction despite having higher transportation emissions [43]. Another notable point in this regard is that many studies only assess the emissions during the transportation of materials or modules to the factory and construction sites while ignoring the reduced number of trips observed in the case of MC owing to its bulk delivery of prepared modules [46]. MC also minimizes the redundant tours of contractors and subcontractors to the construction site owing to better planning and scheduling; hence, sites are visited only when necessary, unlike in conventional construction [60]. Emissions due to the overheads of construction sites are also a significant contributor to GHG emissions that are cut down or largely mitigated in MC [61]. These aspects further advocate MC's utility in lowering the CI's GHG emissions.

The emissions incurred during the building phase owing to equipment use and construction operations are also lower in MC [62]. This is mainly due to optimized resource and equipment allocation in MC, which reduces unnecessary fuel use, resulting in lower emissions [63]. For instance, MC typically requires a smaller on-site workforce than traditional construction. This means fewer commuting workers, fewer idling vehicles, and less equipment at the construction site, reducing emissions [64]. Moreover, MC relies on off-site fabrication, resulting in less on-site equipment and machinery. For example, in MC, materials are often precisely cut off-site, reducing waste and the need for on-site machinery like saws and grinders. This minimizes the use of energy and emissions associated with operating these tools and reduces the transportation of waste materials to landfills, further reducing GHG emissions incurred during the process [63].

Similarly, the end-of-life (EoL) emissions in MC are also lower than in traditional construction, as prefabrication allows design for deconstruction (DfD), which is acclaimed for lower emissions than the deconstruction techniques observed for on-site construction [64]. DfD facilitates the decommissioning of buildings using less carbon-intensive equipment. In contrast, traditionally built structures are demolished using heavy machinery that consumes fuel generously and emits high amounts of GHGs [38]. Moreover, the resources salvaged at the EoL in MC are highly reusable, reducing the demand for raw material production, which is responsible for excessive GHG emissions [62]. These aspects of MC advocate its adoption for CC mitigation as it fosters chances for reducing GHG emissions in the CI.

High GHG emissions attributed to the CI are a key contributor to CC [45]. Curbing the GHG emissions from the built environment remains pivotal in effective CC mitigation [32]. MC paves avenues for CC mitigation by reducing GHG emissions compared to traditional and on-site methods of construction [38]. The controlled environment, factory setting, sustainable materials, and optimized equipment use are the key factors governing the lower GHG emissions of MC, which is instrumental to CC mitigation [65]. Recycling materials and resources in MC is another aspect of reducing embodied emissions in construction as it reduces raw material input [56]. Thus, in light of the existing literature, it can be concluded that MC offers a valuable opportunity for mitigating CC caused by the CI owing to its lower GHG emissions.

In addition to the significant reduction in embodied carbon, the thermal performance of integrated insulation materials in MC is superior to traditionally built structures [66–69]. Li et al. [66] highlighted that in addition to improving the design efficiency and quality of construction, MC also responds to a serious shortcoming of traditional systems, i.e., occupants' comfort, energy savings needs, and design flexibility throughout the building lifecycle. The authors used high insulation panels and aerogel blankets as insulating materials to study integrated building envelopes of modular buildings. The aim was to check the feasibility of climate-responsive "reverse-install" techniques. The results highlighted that MC-based buildings show superior and sustainable thermal performance. Park et al. [67] investigated MC structures regarding energy independence for pertinent usage in disaster scenarios. The authors suggested using different combinations of modular units to achieve superior thermal and energy performance. Yu et al. [68] reviewed the pertinent literature on MC and concluded that such buildings have superior thermal performance when prefabricated facade elements are used for building retrofitting. Similarly, Liu et al. [70] investigated the impact of future climatic changes on modular buildings in Hong Kong. The authors argued that insulations such as thick (0.06–0.1 m) polyurethane foam used in MC provide superior thermal performance and energy efficiency. Further, glazing materials, horizontal shading projection factors, and window-to-wall ratio are immune to future climatic uncertainties.

3.2.2. Curtailing Resource Intensiveness by Enabling a Circular Economy

Enabling a CE in the CI can pave the way for resolving its resource intensiveness through optimized resource production and consumption of resources. A CE aims to cultivate a cradle-to-cradle system in the CI whereby resources are conserved, recycled, and reused to minimize the extraction of raw materials and waste generation. This offers a potential departure from the widely used "Take, Make, Use, Dispose" approach, which is accountable for the inefficient utilization of resources in the CI [41]. MC is regarded as an alluring prospect for implementing a CE in the CI. The synergy between MC and CE principles, as illustrated in Figure 5, has been substantially documented and acclaimed in the existing literature [71].

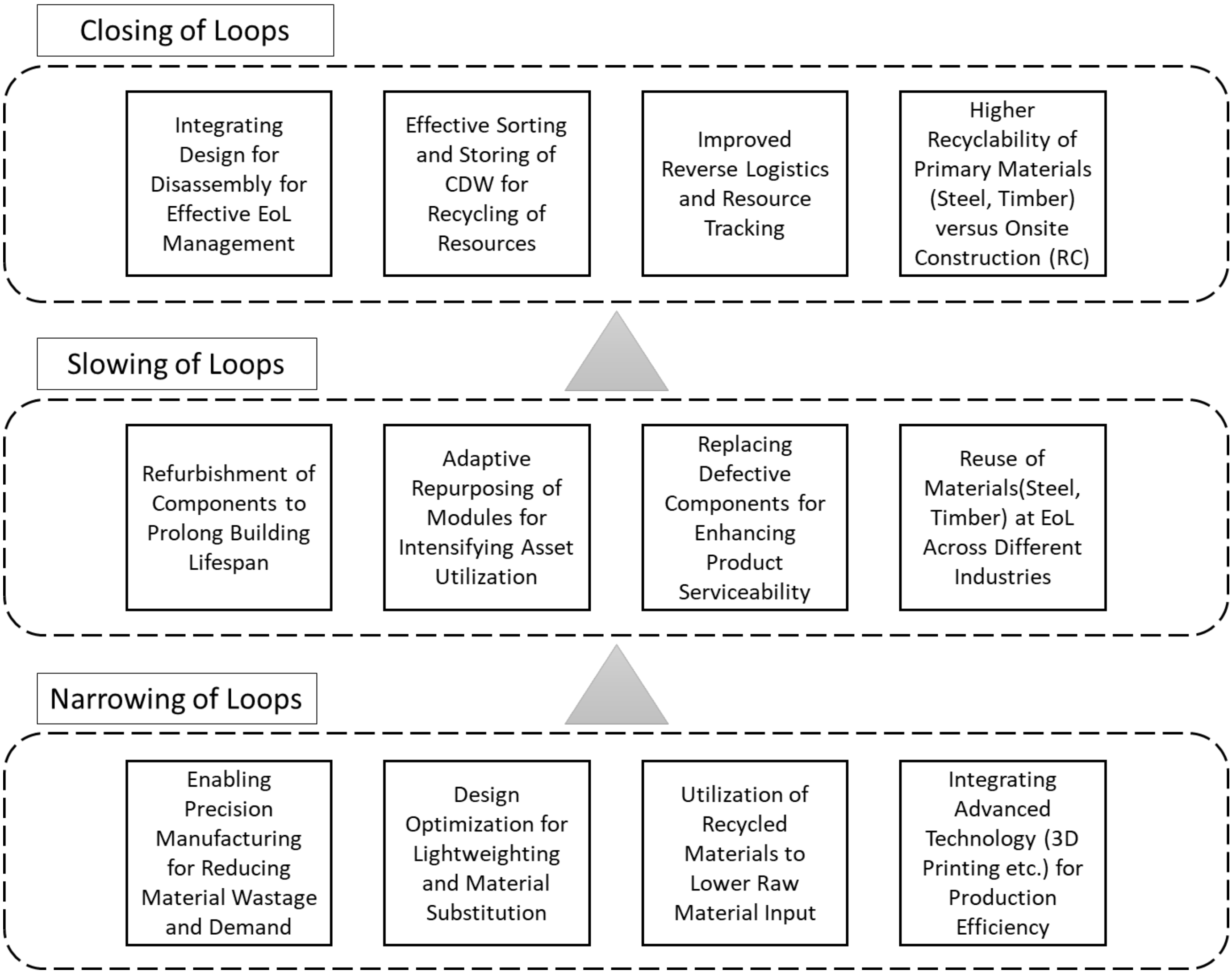

Figure 5. Links between MC and circular economy.

Switching from conventional reinforced concrete to prefabricated modules is projected to bring in a 78% reduction in material consumption. Depending upon the level of prefabrication, MC instigates 20–65% waste minimization through the backflow of resources [72]. Approximately 80% of prefabricated modules can be recycled or reused, underscoring the importance of MC in facilitating CE practices in the CI [72].

MC facilitates the integration of CE principles in construction by actively supporting three core strategies of a CE: (1) narrowing, (2) slowing, and (3) closing the loops. Narrowing the loop is a CE strategy emphasizing fewer resources per product to alleviate the excessive consumption of resources [72]. Reducing the use of natural reserves in the production and consumption of resources is a fundamental tenet of narrowing [7]. MC enables the narrowing of resources by implementing precision manufacturing in construction works. The meticulous fabrication of building components enabled by the factory setting of MC minimizes the generation of construction waste, which in turn lowers the demand for raw materials [73]. Computer numerical control (CNC) machines, 3D printing, and laser cutting are some technologies that are widely used in MC to cut, shape, and mill the construction materials precisely while strictly adhering to the design guidelines, which prevents the excessive use of resources during the fabrication of building components [74]. The standardization of modules produced in off-site construction facilitates the implementation of automated manufacturing systems in construction, effectively reducing variances in the final products and the redundant consumption of resources driven by such variances [73]. The controlled environment available in MC enhances quality control in construction processes, eradicating errors and omissions sustained during the production of modular units. The improved quality control in MC mitigates the need for rework and corrections to rectify errors, thereby fostering an optimized use of resources [74]. MC also contributes to the narrowing of resources by utilizing recycled materials in construction works, lowering the number of new resources used per product. Modular units usually constitute steel or timber as their primary building block instead of reinforced concrete, as in traditional methods. Steel and timber are recycled conveniently on a larger scale than concrete, with a heterogeneous composition calling for a complex recovery process that inhibits recycling [75]. As a result, MC allows the procurement of recycled steel and timber in large volumes to substitute raw materials in construction to narrow the flow of natural resources in CI [75].

Slowing down the resource loop is the CE strategy, which focuses on prolonging the functional lifespan of a product to decelerate the overall consumption of resources [76]. MC contributes to slowing resource consumption by promoting effective refurbishment and maintenance of modules, which helps extend their lifespan [77]. In refurbishment, buildings' outdated and aged components are replaced or renewed through renovation, restoring their serviceability [16]. Refurbishing traditionally built structures is difficult as their components cannot be decommissioned without destructive disassembly [77]. However, different components of modular units are easily detachable owing to their adaptable design, which enables the disassembly of units [64].

Moreover, refurbishing timber and steel-based structures is easier than RC structures, which gives MC an advantage [78]. Resultantly, MC sustains the refurbishment and maintenance of modular units, more so than conventional construction, which extends their service life, slowing down the flow of resources. Another facet of MC that significantly contributes to the deceleration of resource loops is the adaptability inherent in prefabricated buildings. This adaptability allows them to serve various purposes throughout their lifespan [78]. For instance, upon decommissioning of modular structures, their components can be used elsewhere in new or existing modular units through reassembly, which reduces the disposal of construction materials. Similarly, when modular units become outdated and unfit to serve as residential apartments, they can be repurposed with minimal modifications to serve as temporary offices or retail spaces for accommodating businesses without having to construct new buildings [79]. Upon the dismantling of prefabricated units, the recovered materials, such as steel and timber, can be repurposed in diverse industries, including automobiles and furniture. Unlike concrete, which primarily serves the construction industry, steel and timber have diverse applications across various industries [79].

Closing the loops aims to create a regenerative system whereby the use of each resource is maximized by techniques like recycling, reusing, and remanufacturing, extending resources' serviceability [76]. Developing closed-loop systems in the CI has proven to be an uphill task due to multiple barriers like deconstruction difficulty, deficient material traceability, poor reverse logistics of demolished materials, and inefficient management of CDW [80]. However, MC resolves these impediments by fostering the DfD technique that allows for the easy recovery of products, parts, and materials when a building is disassembled or renovated [81]. Construction elements and volumetric units in off-site construction are fabricated following DfD principles, which enables a convenient and efficient disassembly of modular buildings in the later stages of their lifecycle [81]. The efficient deconstruction of modular structures allows up to 70% of the building components to be recycled and reused through take-back mechanisms integral to CE-based business models [82]. The construction of buildings in the form of multiple modules increases material traceability, facilitating their recovery at EoL for renewal and reuse [46]. As a result, modular structures streamline the remanufacturing process, enabling the restoration of products at the end of their lifecycle. This results in a simplified and efficient procedure for reprocessing and renewing products, contributing to the circularity of the MC approach.

Similarly, functional modular products with enduring properties retrieved through nondestructive disassembly procedures are recycled immediately, allowing their repeated use across multiple projects [41]. The CDW generated during the fabrication of construction elements can be efficiently sorted and stored in off-site construction due to the controlled environment of modular factories. Therefore, in contrast to conventional construction practices whereby CDW is often relegated to landfills due to insufficient storage and reverse logistics, MC provides a systematic CDW management approach that facilitates the efficient handling of waste materials, thereby supporting recycling initiatives [73]. Therefore, adopting CE strategies facilitated by MC can alleviate the overconsumption of resources in the CI and contribute to the mitigation of CC.

The CI's unwarranted natural resource consumption actively stimulates CC [83]. Adopting a CE in the CI is essential for alleviating the production of new resources, as the extraction of raw materials and the operations involved in the process are major instigators of CC [83]. MC can uphold CE principles such as narrowing, slowing, and closing the resource loops, making it an instrumental technology in fostering resource efficiency in the CI to reduce CC [82]. From the high recyclability of its building materials to compatibility with DfD, MC enables an efficient consumption of resources across different stages of the project lifecycle, paving the way for CC mitigation [63].

3.2.3. Fomenting Energy Efficiency in Construction

MC can curb excessive energy consumption within the CI to help mitigate CC. As discussed in the previous section, MC upholds a CE, which encourages the recycling and reuse of resources, significantly cutting down the need to produce new construction materials. The production of raw materials is attributed to intensive energy consumption within the CI [84]. According to Yewei and Jing [85], the energy consumption during the production phase of civil building materials constitutes over 80% of the total energy utilized in the construction phase and approximately 10–15% of the entire life cycle of the building. Therefore, by reducing the production of raw materials through CE practices, MC can conserve energy in the CI. Construction equipment operations are optimized in MC owing to the improved project planning. The streamlined use of equipment in MC results in lower fuel consumption and energy leakage in construction activities [86]. The optimization of construction activities is another appreciable aspect of MC, which mitigates redundant tasks in construction projects, thus saving the energy expended on unnecessary processes.

MC allows for a significant reduction, up to 60%, in the execution time of construction projects compared to conventional methods [72]. The swift completion of projects cuts down energy usage associated with overheads and the use of equipment for extended periods, thus encouraging energy efficiency in processes [72]. For example, the assembly time for prefabricated units at the construction site is lower than traditional construction, which trims the energy consumption of equipment such as cranes, rigging equipment, welding instruments, etc. [87]. On-site construction suffers from high variances in desired output during the execution of works, resulting in reworks. However, MC benefits from a controlled environment rendered by its factory setting, which fosters standardized production of building components, largely mitigating variances from the desired output [87]. Consequently, MC requires fewer reworks to omit errors and variances, eradicating energy loss acquired by such surplus activities.

MC can also promote energy efficiency during the operational stage of buildings by improving modular units' insulation [76]. MC can sustain thermally efficient infill materials that significantly reduce the heating and cooling loads of prefabricated structures, accounting for lower energy consumption during the operational stage of buildings [36]. MC also allows for the use of optimized windows and doors for superior insulation on a large scale, owing to the standardization of modular units involved, which cannot be replicated in conventional construction due to the high variability in the design of traditionally built structures [35]. Integrating efficient insulation materials such as glass foam, plastic fiber, and expandable polystyrene into MC is easier than in traditionally built structures, improving thermal performance [77]. The quality control in MC garners tighter seals between building components, which prevents energy leakages, further adding to the energy efficiency of modular buildings [74].

Furthermore, MC sustains passive or alternate energy sources that create opportunities for alleviating the stress imposed on primary energy resources by the CI [78]. Prefabricated buildings are more akin to green roofs, which can decrease buildings' heating, cooling, and ventilation (HVAC) requirements [88]. Solar energy can also be harvested efficiently in modular structures, reducing modular buildings' dependence on conventional energy sources [89]. Cross ventilation designed into the modular units removes the demand for excessive artificial cooling and positively impacts energy consumption [89]. Lastly, the adaptive nature of MC allows for the optimized use of natural light, departing from overdependence on artificial lighting, which contributes to decreasing overall energy consumption [90].

The CI consumes high energy, which is responsible for instigating CC [90]. MC paves the way towards CC mitigation by lowering such energy consumption, which is enabled by the reduced production of raw materials, an acclaimed energy-intensive process [36]. Design optimization, reduced rework due to variances and errors, and integration of passive energy sources and sustainable materials are key contributors to energy-efficient buildings, which are upheld in MC [88]. Owing to the mentioned competencies, MC can effectively mitigate the excessive consumption of energy in the CI and contribute to developing CC resilience.

3.2.4. Fostering Resourceful Land Use and Management

Most of the work is performed on-site in the case of conventional buildings. Local ecosystems, vegetation, and natural habitats are adversely affected because of the intensive land-clearing and site preparation measures required to set up the site for traditional construction [91]. Owing to the expanded spatial requirements of traditional construction, it possesses a substantial horizontal footprint disrupting the adjacent land and environment [90]. On the other hand, MC requires less site clearing and preparation activities as building components are fabricated in a factory. Only prefabricated units are assembled at the site, which necessitates less space than traditional construction, rendering a reduced horizontal footprint for MC [91].

Moreover, with most of the work being performed in an off-site factory, the number of activities performed at the construction site is also significantly reduced in MC. Reducing the on-site activities minimizes the effects of construction works on the adjacent land and environment, leading to their preservation [92]. Landfills consume ample space and valuable land, which poses challenges to effectively utilizing available land, especially in the backdrop of an increasing global population. The CI is a major contributor to landfilling as up to 35% of global landfills constitute waste from the CI [8]. MC is attributed to minimal waste generation and efficient management of CDW owing to the fabrication of construction elements in a controlled factory setting. Therefore, the reduced waste generation observed for MC can also contribute to the depreciation of landfilling, thereby preserving the land for productive utilization [78].

Another factor instigating the inordinate land use by the CI is the unhindered expansion of urban landscapes, which is responsible for habitat loss, fragmentation of ecosystems, and the disruption of biodiversity [93]. Traditional construction adds to this problem because of multiple inherent constraints like a greater spatial footprint and limited vertical growth. While traditional RC structures support high-rise construction when designed to meet this purpose from the inception of a project, they do not offer sufficient options for vertical expansion of existing structures later in their lifecycle [65]. As a result, traditional buildings fail to create useable space later in life due to a lack of vertical expansion, leading to horizontal urban sprawl [94]. Conversely, MC facilitates the vertical expansion of existing structures, paving avenues for high-rise construction due to its adaptive building components [94]. The ability of MC to enable vertical expansion of modular buildings in the later stages of their lifecycle can foster compact and densely populated cities to mitigate the horizontal sprawl of urban areas [95].

Another issue that contributes to excessive land use by cities is the overcrowding of urban areas, causing cities' outward expansion [95]. The deterioration of urban business hubs is strongly linked to factors such as the decentralization of economic activity and the lack of facilities [90]. The rehabilitation and repurposing of brownfields are considered pivotal in curbing the unchecked sprawl of suburbs [40]. MC can contribute to the rejuvenation of brownfields by facilitating infill development. Infill development involves the revitalization of vacant, abandoned, or underutilized land within established communities where infrastructure is already present, serving as a solution for filling gaps and contributing to community revitalization, land conservation, and alternatives to sprawling development [96].

MC enables development within established urban settings by using its reduced horizontal space requirements, which allows construction activities to be carried out in constrained spaces [95]. Moreover, MC's compact design allows for the development of brownfield sites with limited or irregular dimensions. It efficiently utilizes constrained spaces within established urban areas, adding benefits for rejuvenating crumbling city sites [97]. Another aspect of MC that adds to the revitalization of neglected urban areas is its compatibility with adaptive reuse. Adaptive reuse extends the useful life of historic, old, obsolete, and derelict buildings. Adaptive reuse projects seek to maximize the reuse and retention of existing structures and fabrics and improve buildings' economic, environmental, and social performance [98].

Modular structures are highly flexible, allowing for the reconfiguration of structures to meet different purposes. Modules can be amended with minimum renovation to change their functionality depending upon the socio-economic requirements to revitalize the deteriorating neighborhoods in urban areas, enabling effective land use [99]. The adaptive reusability of MC allows it to be utilized for mixed-use projects. Mixed-use projects are essential for optimizing urban space by integrating diverse functions within a single development, promoting efficient land use, and creating vibrant and sustainable cities and communities [100]. Meanwhile, the inflexibility of conventional construction limits the possibilities for adaptive reuse, compelling a linear approach that is not favorable for sustainable land utilization [99]. Therefore, by curbing the unrestrained expansion of cities through smart construction practices and revitalizing existing infrastructure, MC can mitigate inordinate land consumption, which adds to CC.

Unregulated consumption of natural land by the built environment is offsetting the climate. The CI will grow exponentially in the future to accommodate the world's growing population [93]. The subsequent expansion of the built environment will lead to further deterioration of the natural environment, thereby adding to CC [94]. Strategies like infill development and adaptive reuse of existing structures are necessary to promote resourceful land used to repopulate the deteriorating parts of urban areas [96]. Mixed-use projects enabling the same facility to serve multiple purposes are pivotal to avoiding new land preservation construction [100]. MC can enable effective land use and management due to its versatility and reusability. MC's advantages in fostering resourceful land use are summarized visually in Figure 6, which advocates for its importance in CC mitigation.

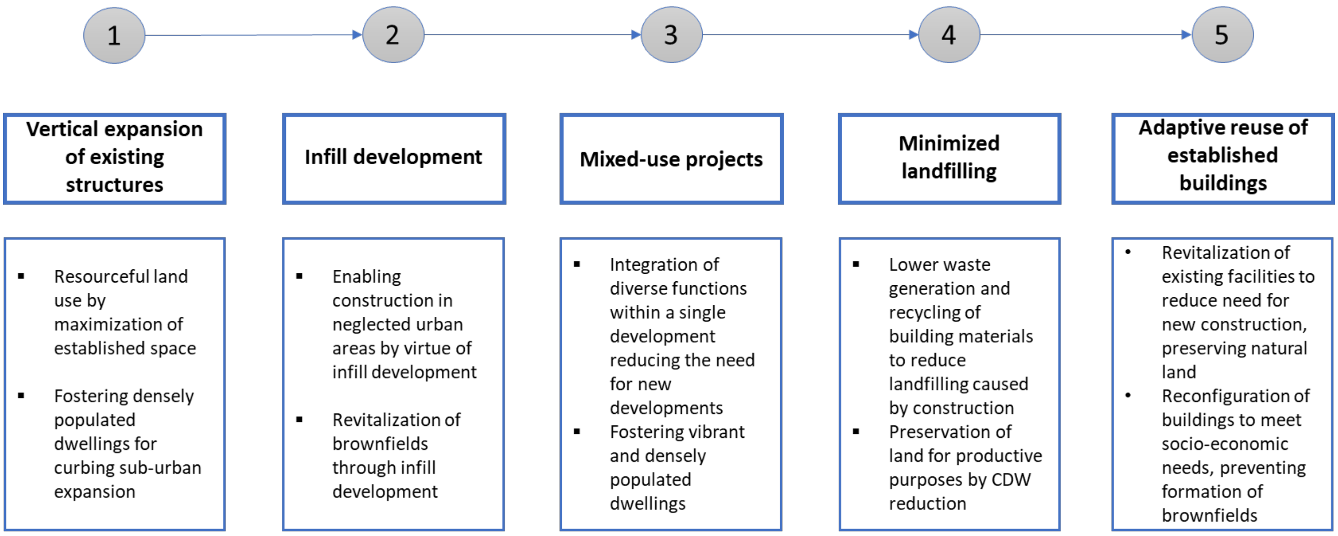

Figure 6. The potential of MC in fostering resourceful land use.

3.2.5. Conceptual Framework for Mitigating Climate Change through Modular Construction

Drawing from the literature review conducted in this study, a conceptual framework is proposed to address the CC induced by CI activities through adopting MC, as illustrated in Figure 7. The proposed framework underscores different MC-based strategies that can reduce GHG emissions, implement resource efficiency by enabling a CE, promote efficient energy consumption, and foster resourceful land use since addressing these parameters is pivotal in mitigating CC [37]. Reducing GHG emissions in the CI requires adopting sustainable construction materials, which the mainstream adoption of MC can enable. The embodied emissions of materials like cement and concrete are exponentially high, rendering traditional construction unsustainable [71]. MC uses concrete in much lower quantities as it predominantly relies on steel and timber for construction, making it much more sustainable in comparison [71].

Moreover, MC is highly compatible with novel materials like recycled plastics, geopolymers, and bamboo, which can further lower the embodied GHG emissions prevalent in the CI [55]. Recycling and reusing building materials is another aspect of MC that can reduce the demand to produce raw materials, substantially lowering embodied emissions. The flexibility of MC facilitates the adaptive reuse of existing modules, which can cut down the need to construct new buildings from the ground up. Curtailing the requirement for new construction can reduce GHG emissions incurred during various phases of construction endeavors [83].

The factory setting and standardized fabrication procedures in MC enable the streamlining of construction activities, which removes redundant exercises and cuts down emissions [38,101]. The fabrication of stackable volumetric units off-site can enable bulk delivery of the prepared modules to the construction site. As a result, the overall number of trips to the construction site can be reduced, lowering the associated emissions [46]. Through a culmination of these strategies enabled by MC, GHG emissions during constriction works can be significantly reduced to alleviate the massive GHG footprint of the CI.

The resource intensiveness of the CI is another instigator of CC, which can be dealt with by employing MC, as shown in Figure 7. MC fosters DfD due to the unique fabrication of its building components, which allow modular units to be detached, allowing for convenient disassembly of modules [102]. As a result, modules are recovered at the EoL, which can be reconfigured for use elsewhere, thereby conserving resources by mitigating the necessity of new construction [81]. DfD enabled by MC creates an opportunity for implementing a take-back or product as a service (PaaS) business model in the CI, which are also enablers of a CE. The building components in modular units are highly standardized in size and specifications. As a result, defective components can be refurbished or replaced conveniently with an element from a recycled module, which contributes to creating a closed-loop system that enables resource efficiency [103].

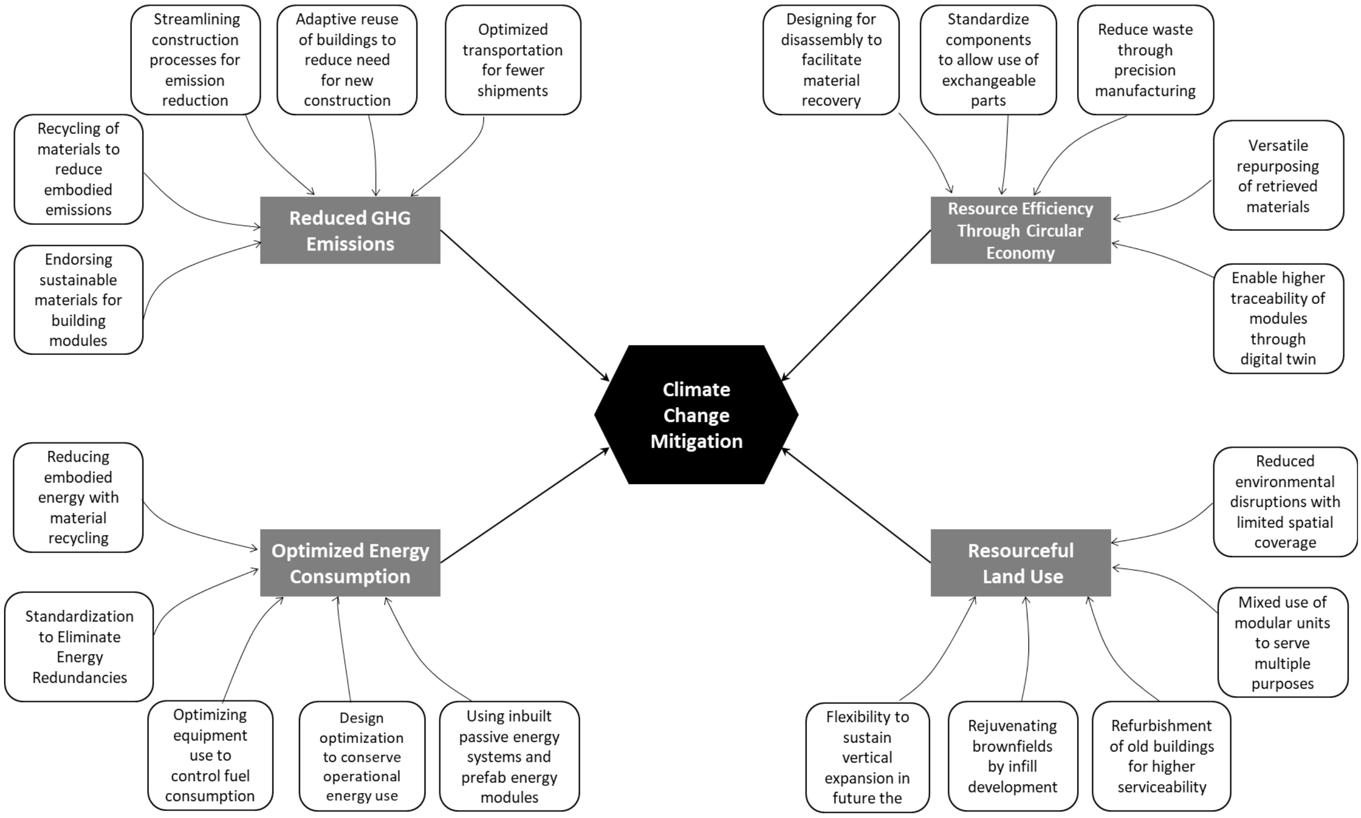

Figure 7. Conceptual framework for mitigating climate change through modular construction.

Precision manufacturing is another MC strategy that reduces CDW generation [104]. The fabrication of components in a controlled setting of a modular factory enables the precise cutting and shaping of materials, leading to minimal resource waste [18]. The controlled environment also enables the effective collection, sorting, and recycling of waste, which can be reconfigured for different purposes. The minimized waste generation, along with its improved recycling, further instates the resource efficiency of MC, emphasizing its allegiance with a CE.

MC can foster superior reverse logistics compared to traditional construction by utilizing technological advancements like artificial intelligence, digital twins, and the Internet of Things (IoT) [105–107]. MC favors material traceability due to labeling its components during production, digital documentation through IoT, or material passports, which aids the reverse logistics of building components at EoL [105]. Blockchain technology is another emerging concept that can be leveraged in MC [108,109]. Traditionally built structures do not favor reverse logistics owing to the highly heterogeneous composition of building materials like concrete, which impedes the traceability of materials for recovery.

MC offers multiple prospects to curb the excessive energy consumption in the CI. The recyclability of materials in MC alleviates the demand for raw material production, which is renowned for being an energy-intensive process [83]. Conserving energy by lowering the extraction and refinement of raw materials is an alluring prospect of MC. During the construction phase of projects, MC can curtail the unwarranted use of energy by eradicating redundant activities and variances due to its standardization of processes [29]. By abolishing unnecessary exercises, construction work is streamlined, eliminating energy leakage in redundant activities. Smart distribution of work packages in MC also enables the optimized use of construction machinery, curtailing equipment's idle running time and lowering their energy consumption [29].

MC can foster energy efficiency during the operation phase of facilities as well. In this regard, a prominent feature of MC is its ability to seamlessly integrate passive energy systems that generate renewable energy, removing excessive dependency on primary energy sources [89]. Photovoltaic (PV) panels can be integrated with modular units conveniently, which can be used to power multiple appliances. Similarly, the modules can be enhanced with green roofs, which regulate temperature within the buildings, cutting down the HVAC requirements [88]. Maximizing sunlight can take away lighting load as well as heating requirements. Optimal choice of windows for specific modular units can mitigate heating and cooling loads by regulating room temperature [22]. By impeding the unwarranted use of energy in the CI, MC can contribute significantly to CC efforts, as enabling energy efficiency is key to sustainable development.

Resourceful land use for the built environment is critical for mitigating CC, and MC can facilitate it in multiple ways. MC is associated with minimized disruptions to the surroundings of a construction site. The horizontal footprint of MC is much less than that of traditional construction, as most of the fabrication is conducted off-site [95]. As a result, MC enables the preservation of the adjacent environment as minimal disruption is caused to surroundings. MC facilitates the vertical expansion of existing structures and new buildings, creating venues for densely populated and centralized urbanization [95]. Such centralization of cities hinders urban sprawl, which can reduce the horizontal expansion of the built environment, thereby preserving natural land, which is crucial for resisting CC.

Another strategy that can be implemented through MC is fostering infill development in neglected urban areas to address their socio-economic needs for revitalization [96]. This feature of MC has alluring implications for promoting effective land use, as the rejuvenation of brownfields can draw people to established areas of the cities, mitigating the need for new construction [94]. MC facilitates mixed-use, which enables modular units to serve different purposes and meet different requirements. MC also facilitates a phased development strategy, providing the flexibility to incrementally introduce new modules or functions. This approach is well-suited for dynamic mixed-use projects, allowing them to evolve, expand, or adapt to shifting demands over time [99]. MC further facilitates versatile and adaptable designs, incorporating diverse functions within a unified structure. For example, a modular building can seamlessly integrate commercial spaces on its lower floors while featuring residential units on the upper levels, emphasizing MC's compatibility with mixed-use projects [99]. Due to this feature, the same buildings or facilities can serve multiple functionalities, thereby trimming down the requirements for new construction to conserve land.

The adaptive nature Inherent to MC allows for the reconfiguration of older modular buildings through refurbishment and renovation. Refurbishing modular buildings is easier as components are easily replaceable, extending the service life of units [85]. As a result, prefabricated units can serve for a longer time, which assists in preserving the natural environment by revitalizing established buildings.

4. Discussion

The findings of the SLR highlight the impact of using MC for CC mitigation in the CI. Studies pointed out that MC can mitigate CC by lowering GHG emissions, alleviating resource intensiveness, curbing inadequate energy consumption, and impeding unwarranted land use in construction.

GHGs are a primary source of CC as they elevate the temperature of Earth at an alarming rate, thereby instigating global warming, which is accountable for the shifting weather patterns and CC [110]. The literature addressing the GHG emissions of MC reports prefabricated construction emits fewer GHGs than on-site construction. In contrast to on-site construction, the lower embodied emissions of materials used in MC (wood, steel, gypsum boards) are the decisive factor that renders it more sustainable than on-site construction [111]. At the product level, very high emissions are reported in the CI, as cement and concrete produce exponentially higher emissions than other building materials. The reduced use of concrete in MC due to its dependence on structural steel and timber lowers GHG emissions [44].

During the construction phase of projects, MC reports lower emissions again due to optimized equipment use and standardized activities, which eradicate redundancies and eliminate emissions incurred in wasteful activities [18].

Streamlining processes and optimizing equipment use in MC contributes to curtailing inadequate energy consumption as well. Idle machinery working is minimized in MC due to the efficient allocation of resources observed in MC [112]. The assembly line approach in MC allows each station of labor and machinery to focus on specific tasks, which increases productivity, renders shorter completion times, and lowers the energy consumption associated with longer project durations of construction. The recyclability of materials and components in MC reduces the need to produce new materials, significantly lowering the CI's embodied energy attributed to raw material production [63]. The compatibility of MC with passive energy systems and optimization of its design for lower energy consumption during the operational stage of buildings nurtures avenues for efficient energy consumption in the construction sector. However, some studies question the viability of using MC in reducing GHG emissions and conserving energy within the CI, implying it has some negative ramifications. For example, MC projects yield higher emissions during the transportation of materials and modules as compared to on-site construction. Research also indicates that MC can emit higher amounts of GHGs when modules are transported longer distances [21]. This aspect of MC can be counter-intuitive to reducing GHG emissions. It is also argued by some studies that life cycle assessments (LCAs) addressing the lower emissions of MC may not be accurate, as off-site emissions have not been effectively quantified for MC in current studies, which predominantly focus on emissions at the construction site [36]. Therefore, some researchers have deemed the existing literature insufficient for holistically capturing the sustainability of MC [111].

Excessive resource consumption by the CI is advancing CC, which can be hampered by promoting a CE as it enables a sustainable approach to resource usage and process efficiency. Studies have documented an improved synergy between MC and CE compared to traditional construction. The modular units and building components retrieved due to DfD can be recycled and reused, minimizing resource waste and upholding a CE. The interchangeable components of modular units allow for convenient refurbishment of defective parts with recycled ones to create a closed-loop system by intensifying the use of established structures [75]. Precision manufacturing enabled through the factory environment of MC facilitates the minimization of waste in fabrication. It also sparks the potential for the recovery of waste, which can be upcycled to serve elsewhere, mitigating the consumption of raw materials.

In comparison, traditional construction hampers the efficient disassembly of facilities at EoL due to the lack of DfD. Further, the heterogeneous composition of on-site construction materials impedes their recycling, leaving downcycling as the only resort for a CE, which is not considered favorable [80,113]. The narrowing, slowing, and closing of resource loops enabled by MC can alleviate the resource intensiveness of the CI by reducing its dependence on raw materials. A report commissioned by the SUN Institute posited that the adoption of a circular economy model could lead to a 32% reduction in primary material consumption by the year 2030 and a 53% reduction by 2050 as compared to the current linear economy paradigm, which reinstates the benefits of MC in this regard [7]. As Europe's urbanization is projected to increase from the current 74% to an estimated 84% by 2050, even modest enhancements in the resource efficiency of the built environment through the promotion of circular economy practices—such as reuse, refurbishment, and material upcycling—can yield substantial environmental benefits [7]. These improvements are pivotal for effectively mitigating the impact of CC.

Inefficient land use practices in the CI, marked by deforestation, habitat disruption, and urban sprawl, result in higher carbon emissions, biodiversity loss, and ecosystem distortion, hastening the progression of CC [114]. Mega housing and construction projects will be undertaken to meet the needs of the growing population, which will further deplete the natural environment through excessive expansion of urban areas. The reviewed literature reports MC as a prospective solution for the problem. The ability of MC to foster vertical expansion of existing structures is critical in rendering efficient land use as it facilitates prospects of accommodating growing populations within established structures, mitigating the horizontal sprawl of cities [16]. The adaptive reuse of modules is also appreciable as the same buildings can be used to meet different needs across their lifecycle, mitigating the need to construct new facilities that conserve urban land. The adaptability of prefabricated units facilitates mixed-use projects, which efficiently use space to perform different functionalities [16,99]. Such projects allow different portions of the same structure to serve varying purposes, which optimizes land use by the built structures. Disruptions to the surroundings and environment, such as clearing trees and mass soil excavation, are reduced in MC due to most work being conducted off-site. Only the assembly of the fabricated units is carried out on-site, which necessitates less space than traditional construction, causing MC to have lower disruptions to the adjacent environment, enabling resourceful land use [115].

The adoption of MC for CC mitigation will contribute to the United Nations' Sustainable Development Goals (UNSDGs) by upholding its multiple facets [116]. As SDG-13 of UNSDGs, i.e., "Climate Action", targets the integration of CC mitigation measures into national policies and planning, MC poses an opportunity to reform the CI by enabling climate-friendly development [59]. The lower GHG emissions of MC can be instrumental in achieving the ambitious target of net zero emissions set by SDG-13, contributing effectively to CC mitigation. With carbon neutrality initiatives gaining momentum in recent years, MC can be a valuable addition to such initiatives as it can potentially offset the high carbon footprint of the CI [92]. Another goal of UNSDGs that MC can uphold is "Responsible Consumption and Production (SDG-12)". The synergy between MC and CE principles is appreciable in the context of optimized consumption of resources. By closing the resource loops in the CI, MC can alleviate the imbalanced resource utilization, thereby contributing to the attainment of targets set by SDG-12 [79]. Moreover, MC has the potential to foster "Sustainable Cities and Communities (SDG-11)" owing to its versatility, adaptive reuse, and ability to sustain vertical expansion [21]. As SDG-11 aims to develop economically, environmentally, and socially sustainable dwellings for humankind, MC can assist by promoting resourceful land use in the CI.

Given the benefits of MC in the context of CC, the CI should aim to facilitate modularization. However, departing from the established norms of the CI, which promote traditional and on-site modes of construction, is an uphill task [43]. Emphasis on acquiring technically skilled professionals well versed in MC is necessary to shift from on-site methods [43]. Developing infrastructure such as modular factories in strategic locations is also pivotal in driving the industry towards MC by making modular products readily accessible to the masses [117]. Repurposing established factories to function as modular factories is another strategy that can be crucial in adopting MC in the CI [117]. Prioritizing vendors, consultants, and contractors with expertise in MC during procurement is highly beneficial for facilitating MC adoption in the CI [118]. At the government level, policies should be devised to incentivize the transition from on-site methods towards prefabrication, and strong legislation should be developed to encourage stakeholder compliance.

5. Conclusions

In the wake of the intensifying climate crisis and its alarming implications, the CI is searching for solutions to attain sustainability in its practices to mitigate CC successfully. This study aims to provide insights into the viability of using MC for developing CC resistance through a holistic literature review. The current study's findings reinstate the sustainability of MC compared to traditional approaches, outlining its propriety in fostering CC mitigation in the CI. The study argues that MC can mitigate the climate crisis by (1) reducing GHG emissions, (2) promoting a CE for resource efficiency, (3) enhancing energy efficiency, and (4) encouraging efficient land use and management.

The study discusses these four aspects in detail, presenting the prevailing literature's findings. The effect of MC on GHG emissions is explored, revealing that the lifecycle emissions of MC projects are much lower than those of traditional construction. This is due to the lower embodied emissions of wood and steel widely used in MC compared to RC concrete, the primary building material in on-site construction. Links between MC and CE are also explored, arguing that the CI's resource intensiveness can be mitigated through MC. As the components of MC are highly reusable, waste is minimized, leading to resource efficiency. The convenience of refurbishment in MC is another aspect that emphasizes the feasibility of developing circular systems in the CI. Prefabrication was revealed to be more energy efficient than on-site methods due to the precision manufacturing, resource allocation, and optimized processes. MC also enables prospects for effective land use through infill development and vertical expansion of existing structures, which can curb the urban sprawl responsible for depleting ecosystems. The study also documents different strategies and measures enabled by MC, which can be implemented to mitigate CC caused by the CI. These include lowering embodied emissions and energy through sustainable materials, upholding DfD for closing resource loops through recycling, and promoting mixed-use projects facilitated by MC to meet the socio-economic necessities for fostering sustainable land use in the CI. A conceptual framework is presented that illustrates MC's role in implementing these CC mitigation strategies.

This study humbly addresses industry practitioners, academic scholars, and policymakers and strives to accentuate the viability of solving the climate crisis caused by the CI through the widespread adoption of MC. The study offers insights into the prospects of fostering sustainable development through MC, which aligns with the UN-SDGs and is pivotal in attaining ambitious goals such as "net zero emissions" by 2050 for effective climate action.

The study has implications for research and practice as it aims to direct the CI's attention toward leveraging MC for effective climate action. It encourages research in various facets of MC, such as using automated systems to further improve its efficiency in the context of Industry 4.0 initiatives, owing to its importance for CC mitigation. It also incites studies aimed at accessing innovative project delivery approaches for MC to facilitate its use in mega projects. This study advocates for MC to be employed to attain sustainable infrastructural development in the CI, thus aiding industry experts. Bringing forth the advantages of MC for CC mitigation can inspire investors to invest in MC, thus paving the way toward a sustainable CI.

The study's limitations include using the Scopus repository only instead of utilizing multiple databases such as Web of Sciences and Google for the data extraction. The existing methods of LCA have been criticized for their inadequacy in comparing the sustainability of MC with on-site construction, which posed an inherent disparity to the literature review. Similarly, the study focuses solely on the viability of MC for enabling CC resistance without considering the financial, regional, technical, and organizational impediments that can be counter-productive to the attempts to facilitate sustainability in the CI. The study also does not differentiate between efforts needed in developing and developed countries and has a more generic approach.

Future studies can look into adding more strategies and ranking and prioritizing the current strategies presented in Figure 7 of this study. Such studies should look to illustrate the bottlenecks preventing the uptake of MC with an emphasis on devising solutions to such hindrances. Improved LCAs should be conducted to investigate the sustainability of MC along with its comparison to other construction techniques for unveiling sustainable techniques and practices to reform the CI. Key performance indicators should be established to indicate the environmental performance of MC projects for promoting climate-responsible development.

Author Contributions: Conceptualization, Z.W.S. and F.U.; methodology, Z.W.S. and F.U.; software, Z.W.S.; validation, Z.W.S., F.U., S.Q. and R.M.; formal analysis, Z.W.S.; investigation, Z.W.S.; resources, F.U., S.Q. and R.M.; data curation, Z.W.S., F.U., S.Q. and R.M.; writing—original draft preparation, Z.W.S. and F.U.; writing—review and editing, F.U., S.Q. and R.M.; visualization, Z.W.S. and F.U.; supervision, F.U., S.Q. and R.M.; project administration, F.U., S.Q. and R.M.; funding acquisition, R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available with the first author and can be shared upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Studies included in the current review article.

ID	Title	Author	Year	Journal
1	Conventional versus modular construction methods: a comparative cradle-to-gate LCA for residential buildings	M. Kamali, K. Hewage, R. Sadiq [24]	2019	*Energy and Buildings*
2	A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: a case of developing country	H. Pervez, Y. Ali, A. Pertillo [43]	2021	*Journal of Cleaner Production*
3	Innovative, modular building facades—as a tool to counteract the effects of and to prevent climate change	P. Kaminska, H. Michalak [119]	2023	*Civil and Environmental Engineering Reports*
4	Assessment of modular construction system made with low environmental impact construction materials for achieving sustainable housing projects	G. Romero, M. Javier, C. Rojas, K. Rodriguez [35]	2023	*Sustainability*
5	Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: the "moby" case study	V. Tavares, N. Lacerda, F. Freire [46]	2019	*Journal of Cleaner Production*
6	Climate change and the energy performance of buildings in the future—a case study for prefabricated buildings in the UK	F. Ismail, F. Haji, S. Donyavi, P. Boyd, D. Sohrab [120]	2021	*Journal of Building Engineering*
7	Circular economy strategies in modern timber construction as a potential response to climate change	M. Ghobadi, S. Sepasgozar [121]	2023	*Journal of Building Engineering*
8	Is it a possibility to achieve energy plus prefabricated building worldwide?	A. Alkhalidi, A. Abuothman, A. Aldweik, A. Al-Baaz [122]	2021	*International Journal of Low-Carbon Technologies*
9	Sustainability in modular design and construction: a case study of 'the stack'	Y. Ahn, K. Kim [123]	2014	*International Journal of Sustainable Building Technology and Urban Development*
10	Timber-based façades with different connections and claddings: assessing materials' reusability, water use and global warming potential	M. Juaristi, I. Sebastiani, S. Avesani [124]	2022	*Journal of Facade Design and Engineering*
11	New residential construction building and composite post and beam structure toward global warming mitigation	A. Balasbaneh, A. Marsono [125]	2018	*Environmental Progress and Sustainable Energy*
12	Carbon emission reduction in prefabrication construction during materialization stage: a BIM-based life-cycle assessment approach	J. Hao, B. Cheng, W. Lu, J. Xu, J. Wang, W. Bu, Z. Guo [126]	2020	*Science of the Total Environment*
13	Thirty years of climate mitigation: lessons from the 1989 options appraisal for the UK	E. Lees, N. Eyre [127]	2021	*Energy Efficiency*

Table A1. *Cont.*

ID	Title	Author	Year	Journal
14	Comparative analysis of off-site precast concrete and cast-in-place concrete in low-carbon built environment	C. Liu, F. Zhang, H. Zhang [128]	2020	*Fresenius Environmental Bulletin*
15	Numerical study on the thermal performance of lightweight temporary building integrated with phase change materials	L. Zhu, Y. Yang, S. Chen, Y. Sun [129]	2018	*Applied Thermal Engineering*
16	Minimizing upfront carbon emissions of steel-framed modular housing: a case study	S. Kechidi, N. Banks [130]	2023	*Journal of Building Engineering*
17	Design and prototyping of a FRCC modular and climate responsive affordable housing system for underserved people in the pacific island nations	D. Rockwood, J. Silva, S. Olsen, I. Robertson, T. Tran [131]	2015	*Journal of Building Engineering*
18	Systematic review on the integration of building information modelling and prefabrication construction for low-carbon building delivery	S. Yevu, E. Owusu, A. Chan, K. Sarpong [132]	2023	*Building Research and Information*
19	Air temperature cooling by extensive green roofs in Toronto Canada	J. MacIvor, L. Margolis, M. Perotto, J. Drake [133]	2016	*Ecological Engineering*
20	The mediterranean smart adaptive wall. An experimental design of a smart and adaptive facade module for the mediterranean climate	M. Iommi [134]	2018	*Energy and Buildings*
21	Finite element study of hyperstructure systems with modular light-frame construction in high-rise buildings	N. Labrecque, S. Ménard M. Oudjene, P. Blanchet [135]	2022	*Buildings*
22	Analytical solutions for the dynamic analysis of a modular floating structure for urban expansion	S. Wang [136]	2022	*Ocean Engineering*
23	The carbon emission assessment of a building with different prefabrication rates in the construction stage	Q. Han, J. Chang, G. Liu, H. Zhang [137]	2022	*International Journal of Environmental Research and Public Health*
24	Rapid deployment modular building solutions and climatic adaptability: case based study of a novel approach to "thermal capacity on demand"	B. Ceranic, J. Beardmore, A. Cox [138]	2018	*Energy and Buildings*
25	Carbon emission energy management analysis of LCA-based fabricated building construction	L. Luo, Y. Chen [139]	2020	*Sustainable Computing: Informatics and Systems*
26	City regeneration through modular phase change materials (PCM) envelopes for climate neutral buildings	J. Messana, V. Lopez, T. Pellicer [140]	2022	*Sustainability (Switzerland)*
27	A research methodology for mitigating climate change in the restoration of buildings: rehabilitation strategies and low-impact prefabrication in the "El Rodezno" water mill	A. Carranza, R. Anon-Abajas, G. Lamela [141]	2021	*Sustainability (Switzerland)*
28	Design and climate-responsiveness performance evaluation of an integrated envelope for modular prefabricated buildings	W. Wang., J. Huang, S. Lu, J. Li [66]	2018	*Advances in Materials Science and Engineering*
29	Exploring the potential of climate-adaptive container building design under future climates scenarios in three different climate zones	J. Shen., B. Copertaro, X. Zhang, J. Koke [142]	2020	*Sustainability (Switzerland)*
30	BIM-based building geometric modeling and automatic generative design for sustainable off-site construction	V. Gan [143]	2022	*Journal of Construction Engineering and Management*
31	Life cycle and energy performance assessment of three wall types in south-eastern Europe region	N. Maodus, B. Agarski, I. Budak, M. Radeka [144]	2016	*Energy and Buildings*

References

1. Akter, S. Australia's Black Summer wildfires recovery: A difference-in-differences analysis using nightlights. *Glob. Environ. Change* **2023**, *83*, 102743. [CrossRef]
2. Waseem, H.B. Floods in Pakistan: A state-of-the-art review. *Nat. Hazards Res.* **2023**, *3*, 359–373. [CrossRef]
3. Wake, B. Buildings at risk. *Nat. Clim. Chang.* **2021**, *11*, 642. [CrossRef]
4. Lenzen, M.; Malik, A.; Kenway, S.; Daniels, P.; Lam, K.L.; Geschke, A.J.N.H.; Sciences, E.S. Economic damage and spillovers from a tropical cyclone. *Nat. Hazards Earth Syst. Sci.* **2019**, *19*, 137–151. [CrossRef]
5. Fawzy, S.; Osman, A.I.; Doran, J.; Rooney, D.W. Strategies for mitigation of climate change: A review. *Environ. Chem. Lett.* **2020**, *18*, 2069–2094. [CrossRef]
6. Fernandez, G.; Ahmed, I. "Build back better" approach to disaster recovery: Research trends since 2006. *Prog. Disaster Sci.* **2019**, *1*, 100003. [CrossRef]
7. Gallego-Schmid, A.; Chen, H.M.; Sharmina, M.; Mendoza, J.M.F. Links between circular economy and climate change mitigation in the built environment. *J. Clean. Prod.* **2020**, *260*, 121115. [CrossRef]
8. Oyedele, L.O.; Ajayi, S.O.; Kadiri, K.O. Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resour. Conserv. Recycl.* **2014**, *93*, 23–31. [CrossRef]
9. Dimoudi, A.; Tompa, C. Energy and environmental indicators related to construction of office buildings. *Resour. Conserv. Recycl.* **2008**, *53*, 86–95. [CrossRef]
10. Assaad, R.H.; El-adaway, I.H.; Hastak, M.; LaScola Needy, K. The COVID-19 pandemic: A catalyst and accelerator for offsite construction technologies. *J. Manag. Eng.* **2022**, *38*, 04022062. [CrossRef]
11. Tunji-Olayeni, P.F.; Omuh, I.O.; Afolabi, A.O.; Ojelabi, R.A.; Eshofonie, E.E. Climate change mitigation and adaptation strategies for construction activities within planetary boundaries: Limitations of developing countries. *J. Phys. Conf. Ser.* **2019**, *1299*, 012006. [CrossRef]
12. Zhou, J.; Ren, D. A hybrid model of external environmental benefits compensation to practitioners for the application of prefabricated con-struction. *Environ. Impact Assess. Rev.* **2020**, *81*, 106358. [CrossRef]
13. Roy, K. 'Build back Better' Requires a Framework That Focuses on the Full Life of a House—From Materials to its End of Life. Available online: https://theconversation.com/build-back-better-requires-a-framework-that-focuses-on-the-full-life-of-a-house-from-materials-to-its-end-of-life-203325 (accessed on 7 January 2024).
14. Masood, R.; Lim, J.B.; González, V.A.; Roy, K.; Khan, K.I.A. A systematic review on supply chain management in prefabricated house-building research. *Buildings* **2022**, *12*, 40. [CrossRef]
15. Lu, N. The Current Use of Offsite Construction Techniques in the United States Construction Industry. In *Building a Sustainable Future, Proceedings of the 2009 Construction Research Congress, Construction Institute of American Society of Civil Engineers. Seattle, WA, USA, 5–7 April 2009*; American Society of Civil Engineers: Reston, VA, USA, 2009; pp. 946–955. [CrossRef]
16. Jaillon, L.; Poon, C.S. Sustainable construction aspects of using prefabrication in dense urban environment: A Hong Kong case study. *Constr. Manag. Econ.* **2008**, *26*, 953–966. [CrossRef]
17. Thurairajah, N.; Rathnasinghe, A.; Ali, M.; Shashwat, S. Unexpected Challenges in the Modular Construction Implementation: Are UK Contractors Ready? *Sustainability* **2023**, *15*, 8105. [CrossRef]
18. O'Connor, J.T.; O'Brien, W.J.; Choi, J.O. Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization. *J. Constr. Eng. Manag.* **2014**, *140*, 04014012. [CrossRef]
19. Pan, W.; Gibb, A.F.; Dainty, A.R.J. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Constr. Manag. Econ.* **2007**, *25*, 183–194. [CrossRef]
20. Sandamini, K.Y.; Waidyasekara, K.G.A.S.; Weerapperuma, U.S. Cost-benefits of relocatable modular buildings (RMB) for construction site offices: The case of Sri Lanka. *FARU J.* **2023**, *10*, 29–38. [CrossRef]
21. Karthik, S.; Sharareh, K.; Behzad, R. Modular Construction vs. Traditional Construction: Advantages and Limitations: A Comparative Study. *Creat. Constr. Conf.* **2020**, *12*, 11–19. [CrossRef]
22. Ferdous, W.; Bai, Y.; Ngo, T.D.; Manalo, A.; Mendis, P. New advancements, challenges and opportunities of multi-storey modular buildings—A state-of-the-art review. *Eng. Struct.* **2019**, *183*, 883–893. [CrossRef]
23. Lacey, A.W.; Chen, W.; Hao, H.; Bi, K. Structural response of modular buildings—An overview. *J. Build. Eng.* **2018**, *16*, 45–56. [CrossRef]
24. Kamali, M.; Hewage, K.; Sadiq, R. Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. *Energy Build.* **2019**, *204*, 109479. [CrossRef]
25. Hořínková, D. Advantages and disadvantages of modular construction, including environmental impacts. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1203*, 32002. [CrossRef]
26. Jokisalo, J.; Kurnitski, J.; Korpi, M.; Kalamees, T.; Vinha, J. Building leakage, infiltration, and energy performance analyses for Finnish detached houses. *Build. Environ.* **2009**, *44*, 377–387. [CrossRef]
27. Gunawarden, T.; Mendis, P. Prefabricated Building Systems—Design and Construction. *Encyclopedia* **2022**, *2*, 70–95. [CrossRef]
28. Innella, F.; Arashpour, M.; Bai, Y. Lean Methodologies and Techniques for Modular Construction: Chronological and Critical Review. *J. Constr. Eng. Manag.* **2019**, *145*, 04019076. [CrossRef]
29. Lim, Y.W.; Ling, P.C.H.; Tan, C.S.; Chong, H.Y.; Thurairajah, A. Planning and coordination of modular construction. *Autom. Constr.* **2022**, *141*, 104455. [CrossRef]

30. Olawumi, T.O.; Chan, D.W.M.; Ojo, S.; Yam, M.C.H. Automating the modular construction process: A review of digital technologies and future directions with blockchain technology. *J. Build. Eng.* **2022**, *46*, 103720. [CrossRef]
31. Iqbal, F.; Ahmed, S.; Amin, F.; Qayyum, S.; Ullah, F. Integrating BIM–IoT and Autonomous Mobile Robots for Construction Site Layout Printing. *Buildings* **2023**, *13*, 2212. [CrossRef]
32. Wuni, I.Y.; Shen, G.Q. Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies. *J. Clean. Prod.* **2020**, *249*, 119347. [CrossRef]
33. Masood, R.; Lim, J.B.; González, V.A. Society. Performance of the supply chains for New Zealand prefabricated house-building. *Sustain. Cities Soc.* **2021**, *64*, 102537. [CrossRef]
34. Quale, J.; Eckelman, M.J.; Williams, K.W.; Sloditskie, G.; Zimmerman, J.B. Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *J. Ind. Ecol.* **2012**, *16*, 243–253. [CrossRef]
35. Romero Quidel, R.G.; Soto Acuña, M.J.; Rojas Herrera, C.J.; Rodríguez Neira, K.; Cárdenas-Ramírez, J.P. Assessment of Modular Construction System Made with Low Environmental Impact Construction Materials for Achieving Sustainable Housing Projects. *Sustainability* **2023**, *15*, 8386. [CrossRef]
36. Greer, F.; Horvath, A. Modular construction's capacity to reduce embodied carbon emissions in California's housing sector. *Build. Environ.* **2023**, *240*, 110432. [CrossRef]
37. Akadiri, P.O.; Chinyio, E.A.; Olomolaiye, P.O. Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. *Buildings* **2012**, *2*, 126–152. [CrossRef]
38. Wrigley, P.A.; Wood, P.; O'Neill, S.; Hall, R.; Robertson, D. Off-site modular construction and design in nuclear power: A systematic literature review. *Prog. Nucl. Energy* **2021**, *134*, 103664. [CrossRef]
39. Ullah, F.; Qayyum, S.; Thaheem, M.J.; Al-Turjman, F.; Sepasgozar, S.M.E. Risk management in sustainable smart cities governance: A TOE framework. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120743. [CrossRef]
40. Akhimien, N.G.; Latif, E.; Hou, S.S. Application of circular economy principles in buildings: A systematic review. *J. Build. Eng.* **2021**, *38*, 102041. [CrossRef]
41. Yang, M. Circular economy strategies for combating climate change and other environmental issues. *Environ. Chem. Lett.* **2022**, *21*, 55–80. [CrossRef]
42. Luo, H.; Liu, J.; Li, C.; Chen, K.; Zhang, M. Ultra-rapid delivery of specialty field hospitals to combat COVID-19: Lessons learned from the Leishenshan Hospital project in Wuhan. *Autom. Constr.* **2020**, *119*, 103345. [CrossRef]
43. Pervez, H.; Ali, Y.; Petrillo, A. A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *J. Clean. Prod.* **2021**, *294*, 126210. [CrossRef]
44. Kamali, M.; Hewage, K. Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. *J. Clean. Prod.* **2017**, *142*, 3592–3606. [CrossRef]
45. Vijayavenkataraman, S.; Iniyan, S.; Goic, R. A review of climate change, mitigation and adaptation. *Renew. Sustain. Energy Rev.* **2012**, *16*, 878–897. [CrossRef]
46. Tavares, V.; Soares, N.; Raposo, N.; Marques, P.; Freire, F. Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *J. Build. Eng.* **2021**, *41*, 102705. [CrossRef]
47. Attia, P.M. Reducing embodied carbon emissions of concrete modules in high-rise buildings through structural design optimisation. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1101*, 22023. [CrossRef]
48. Biricik, Ö.; Aytekin, B.; Mardani, A. Effect of waste binder material usage rate on thixotropic behaviour of cementitious systems. *Constr. Build. Mater.* **2023**, *403*, 133197. [CrossRef]
49. Denman, M.; Ullah, F.; Qayyum, S.; Olatunji, O. Post-Construction Defects in Multi-Unit Australian Dwellings: An Analysis of the Defect Type, Causes, Risks, and Impacts. *Buildings* **2024**, *14*, 231. [CrossRef]
50. Belaïd, F. How does concrete and cement industry transformation contribute to mitigating climate change challenges? *Resour. Conserv. Recycl. Adv.* **2022**, *15*, 200084. [CrossRef]
51. Iuorio, O.; Napolano, L.; Fiorino, L.; Landolfo, R. The environmental impacts of an innovative modular lightweight steel system: The Elissa case. *J. Clean. Prod.* **2019**, *238*, 117905. [CrossRef]
52. Dong, Y.H.; Jaillon, L.; Chu, P.; Poon, C.S. Comparing carbon emissions of precast and cast-in-situ construction methods—A case study of high-rise private building. *Constr. Build. Mater.* **2015**, *99*, 39–53. [CrossRef]
53. Hart, J.; D'Amico, B.; Pomponi, F. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *J. Ind. Ecol.* **2021**, *25*, 403–418. [CrossRef]
54. Wolf, C.D.; Hoxha, E.; Hollberg, A.; Fivet, C.; Ochsendorf, J. Database of Embodied Quantity Outputs: Lowering Material Impacts through Engineering. *J. Archit. Eng.* **2020**, *26*, 4020016. [CrossRef]
55. Bhaliya, P.; Rajgor, M.; Shah, D.A. Evaluation of Feasibility for Novel Modular Block Construction. *ECS Trans.* **2022**, *107*, 4011–4020. [CrossRef]
56. Rinne, R.; Ilgın, H.E.; Karjalainen, M. Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. *Int. J. Environ. Res. Public Health* **2022**, *19*, 774. [CrossRef] [PubMed]
57. Bahrami, A.; Olsson, M.; Svensson, K. Carbon Dioxide Emissions from Various Structural Frame Materials of Single-Family Houses in Nordic Countries. *Int. J. Innov. Res. Sci. Stud.* **2022**, *5*, 112–120. [CrossRef]
58. Boafo, F.E.; Kim, J.H.; Kim, J.T. Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways. *Sustainability* **2016**, *8*, 558. [CrossRef]

59. Cao, X.; Li, X.; Zhu, Y.; Zhang, Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J. Clean. Prod.* **2015**, *109*, 131–143. [CrossRef]
60. Labaran, Y.H.; Mathur, V.S.; Muhammad, S.U.; Musa, A.A. Carbon footprint management: A review of construction industry. *Clean. Eng. Technol.* **2022**, *9*, 100531. [CrossRef]
61. Biswas, W.K. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *Int. J. Sustain. Built Environ.* **2014**, *3*, 179–186. [CrossRef]
62. Du, Q.; Bao, T.; Li, Y.; Huang, Y.; Shao, L. Impact of prefabrication technology on the cradle-to-site CO_2 emissions of residential buildings. *Clean Technol. Environ. Policy* **2019**, *21*, 1499–1514. [CrossRef]
63. Aghasizadeh, S.; Tabadkani, A.; Hajirasouli, A.; Banihashemi, S. Environmental and economic performance of prefabricated construction: A review. *Environ. Impact Assess. Rev.* **2022**, *97*, 106897. [CrossRef]
64. Roberts, M.; Allen, S.; Clarke, J.; Searle, J.; Coley, D. Understanding the global warming potential of circular design strategies: Life cycle assessment of a design-for-disassembly building. *Sustain. Prod. Consum.* **2023**, *37*, 331–343. [CrossRef]
65. Paudel, P.; Dulal, S.; Bhandari, M.; Tomar, A.K. Study on Pre-fabricated Modular and Steel Structures. *Int. J. Civ. Eng.* **2019**, *3*, 8–15. [CrossRef]
66. Li, J.; Lu, S.; Wang, W.; Huang, J.; Chen, X.; Wang, J. Design and climate-responsiveness performance evaluation of an integrated envelope for modular prefabricated buildings. *Adv. Mater. Sci. Eng.* **2018**, *2018*, 8082368. [CrossRef]
67. Park, B.; Cho, J.; Jeong, Y. Thermal performance assessment of flexible modular housing units for energy independence following disasters. *Sustainability* **2019**, *11*, 5561. [CrossRef]
68. Yu, S.; Liu, Y.; Wang, D.; Bahaj, A.S.; Wu, Y.; Liu, J. Review of thermal and environmental performance of prefabricated buildings: Implications to emission reductions in China. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110472. [CrossRef]
69. Lin, Z.; Hong, T.; Xu, X.; Chen, J.; Wang, W. Evaluating energy retrofits of historic buildings in a university campus using an urban building energy model that considers uncertainties. *Sustain. Cities Soc.* **2023**, *95*, 104602. [CrossRef]
70. Liu, S.; Wang, Y.; Liu, X.; Yang, L.; Zhang, Y.; He, J. How does future climatic uncertainty affect multi-objective building energy retrofit decisions? Evidence from residential buildings in subtropical Hong Kong. *Sustain. Cities Soc.* **2023**, *92*, 104482. [CrossRef]
71. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
72. Loizou, L.; Barati, K.; Shen, X.; Li, B. Quantifying Advantages of Modular Construction: Waste Generation. *Buildings* **2021**, *11*, 622. [CrossRef]
73. Zhang, Y.; Pan, W. Reducing Construction Waste through Modular Construction. In Proceedings of the 26th International Symposium on Advancement of Construction Management and Real Estate, CRIOCM 2021, Beijing, China, 20–22 November 2021; Guo, H., Fang, D., Lu, W., Peng, Y., Eds.; Springer: Singapore, 2022; pp. 339–347.
74. Zhang, Y.; Pan, W. Quality Control in Modular Construction Manufacturing During COVID-19: Process and Management Standardization. In Proceedings of the 27th International Symposium on Advancement of Construction Management and Real Estate, CRIOCM 2022, Hong Kong, China, 5–6 December 2022; Li., J., Lu, W., Peng, Y., Yuan, H., Wang, D., Eds.; Springer: Singapore, 2023; pp. 1437–1447.
75. Martínez-Muñoz, D.; Martí, J.V.; Yepes, V. Comparative Life Cycle Analysis of Concrete and Composite Bridges Varying Steel Recycling Ratio. *Materials* **2021**, *14*, 4218. [CrossRef] [PubMed]
76. Kirchherr, J.; Yang, N.H.N.; Schulze-Spüntrup, F.; Heerink, M.J.; Hartley, K. Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resour. Conserv. Recycl.* **2023**, *194*, 107001. [CrossRef]
77. Torres, J. Plug and Play Modular Façade Construction System for Renovation for Residential Buildings. *Buildings* **2021**, *11*, 419. [CrossRef]
78. MacKenbach, S.; Zeller, J.C.; Osebold, R. A Roadmap towards Circularity—Modular Construction as a Tool for Circular Economy in the Built Environment. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *558*, 052027. [CrossRef]
79. Garusinghe, G.D.A.U.; Perera, B.A.K.S.; Weerapperuma, U.S. Integrating Circular Economy Principles in Modular Construction to Enhance Sustainability. *Sustainability* **2023**, *15*, 11730. [CrossRef]
80. Kirchherr, J. Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecol. Econ.* **2018**, *150*, 246–272. [CrossRef]
81. Rios, F.C.; Chong, W.K.; Grau, D. Design for Disassembly and Deconstruction—Challenges and Opportunities. *Procedia Eng.* **2015**, *118*, 1296–1304. [CrossRef]
82. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resour. Conserv. Recycl.* **2020**, *160*, 104855. [CrossRef]
83. Schraven, D.; Bukvić, U.; Maio, F.D.; Hertogh, M. Circular transition: Changes and responsibilities in the Dutch stony material supply chain. *Resour. Conserv. Recycl.* **2019**, *150*, 104359. [CrossRef]
84. Dixit, M.K. Embodied energy analysis of building materials: An improved IO-based hybrid method using sectoral disaggregation. *Energy* **2017**, *124*, 46–58. [CrossRef]
85. Yuefei, L.; Jing, L. Research on Regional Difference of Energy Consumption in Production Stage of Civil Building Materials based on Theil Index. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *647*, 012032. [CrossRef]
86. Hong, B. General Optimization Model of Modular Equipment Selection and Serialization for Shale Gas Field. *Front. Energy Res.* **2021**, *9*, 711974. [CrossRef]

87. Thirunavukkarasu, K. Sustainable performance of a modular building system made of built-up cold-formed steel beams. *Buildings* **2021**, *11*, 460. [CrossRef]
88. Sfakianaki, A.; Pagalou, E.; Pavou, K.; Santamouris, M.; Assimakopoulos, M.N. Theoretical and experimental analysis of the thermal behaviour of a green roof system installed in two residential buildings in Athens, Greece. *Int. J. Energy Res.* **2009**, *33*, 1059–1069. [CrossRef]
89. Ju, X. Application of Building Integrated Active and Passive Solar Technology in Harsher Climate Area--Design of the Central Control Building of PV Demonstration Area in Turpan Area, Xinjiang Uygur Autonomous Region, China. *Energy Procedia* **2014**, *57*, 1659–1668. [CrossRef]
90. Abbasi, A.; Saberi, V.; Eghbali, H.; Saberi, H. Views from construction professionals on hospital project construction management using modular prefabricated materials and building information modeling support. *Archit. Struct. Constr.* **2023**, 1–15. [CrossRef]
91. Li, J.; Andersen, L.V.; Hudert, M.M. The Potential Contribution of Modular Volumetric Timber Buildings to Circular Construction: A State-of-the-Art Review Based on Literature and 60 Case Studies. *Sustainability* **2023**, *15*, 16203. [CrossRef]
92. Nabi, M.A.; El-adaway, I.H. Modular Construction: Determining Decision-Making Factors and Future Research Needs. *J. Manag. Eng.* **2020**, *36*, 04020085. [CrossRef]
93. Rahman, G.; Chandio, N.H.; Moazzam, M.F.U.; Ansari, N.A. Urban expansion impacts on agricultural land and thermal environment in Larkana, Pakistan. *Front. Environ. Sci.* **2023**, *11*, 1115553. [CrossRef]
94. Mandeli, K. Public space and the challenge of urban transformation in cities of emerging economies: Jeddah case study. *Cities* **2019**, *95*, 102409. [CrossRef]
95. Thai, H.T.; Ngo, T.; Uy, B. A review on modular construction for high-rise buildings. *Structures* **2020**, *28*, 1265–1290. [CrossRef]
96. Aly, S.S.; Attwa, Y.A. Infill Development As An Approach For Promoting Compactness Of Urban Form. *WIT Trans. Ecol. Environ.* **2013**, *173*, 455–466. [CrossRef]
97. Na, S.; Kim, S.; Moon, S. Additive manufacturing (3D Printing)-applied construction: Smart node system for an irregular building façade. *J. Build. Eng.* **2022**, *56*, 104743. [CrossRef]
98. Shahi, S.; Esfahani, M.E.; Bachmann, C.; Haas, C. A definition framework for building adaptation projects. *Sustain. Cities Soc.* **2020**, *63*, 102345. [CrossRef] [PubMed]
99. Farjam, R.; Motlaq, S.M.H. Does urban mixed use development approach explain spatial analysis of inner city decay? *J. Urban Manag.* **2019**, *8*, 245–260. [CrossRef]
100. Wu, G. Factors influencing the application of prefabricated construction in China: From perspectives of technology promotion and cleaner production. *J. Clean. Prod.* **2019**, *219*, 753–762. [CrossRef]
101. Ghannad, P.; Lee, Y.-C.; Choi, J.O. Investigating Stakeholders' Perceptions of Feasibility and Implications of Modular Construction-Based Post-Disaster Reconstruction. In Proceedings of the Modular and Offsite Construction (MOC) Summit Proceedings, Edmonton, AB, Canada, 21–24 May 2019; pp. 504–513.
102. Wang, X.; Zhou, Z.; Lv, X.; Yang, L.; Yuan, P.F.; Chen, L. Intelligent renovation of existing Olympic venues: Digital design and construction strategy of a DfD-based prefabricated structure system. *Archit. Intell.* **2023**, *2*, 4. [CrossRef]
103. Fernandes, J.; Ferrão, P. A New Framework for Circular Refurbishment of Buildings to Operationalize Circular Economy Policies. *Environments* **2023**, *10*, 51. [CrossRef]
104. Lawson, R.M.; Ogden, R.G.; Bergin, R. Application of modular construction in high-rise buildings. *J. Archit. Eng.* **2012**, *18*, 148–154. [CrossRef]
105. Ding, L.; Wang, T.; Chan, P.W. Forward and reverse logistics for circular economy in construction: A systematic literature review. *J. Clean. Prod.* **2023**, *388*, 135981. [CrossRef]
106. Aslam, B.; Maqsoom, A.; Inam, H.; Basharat, M.u.; Ullah, F. Forecasting Construction Cost Index through Artificial Intelligence. *Societies* **2023**, *13*, 219. [CrossRef]
107. Ullah, F. *Towards Smart Tech 4.0 in the Built Environment: Applications of Disruptive Digital Technologies in Smart Cities, Construction, and Real Estate*; Multidisciplinary Digital Publishing Institute (MDPI): Basel, Switzerland, 2023.
108. Sharma, P.; Tyagi, S.S. C4 Model to manage pandemic using machine learning Curate | Compare | Calculate | Curb. *Int. J. Grid Distrib. Comput.* **2020**, *13*, 1882–1898.
109. Ullah, F.; Al-Turjman, F. Applications. A conceptual framework for blockchain smart contract adoption to manage real estate deals in smart cities. *Neural Comput. Appl.* **2023**, *35*, 5033–5054. [CrossRef]
110. Hossain, M.U.; Sohail, A.; Ng, S.T. Developing a GHG-based methodological approach to support the sourcing of sustainable construction materials and products. *Resour. Conserv. Recycl.* **2019**, *145*, 160–169. [CrossRef]
111. Jang, H.; Ahn, Y.; Roh, S. Comparison of the Embodied Carbon Emissions and Direct Construction Costs for Modular and Conventional Residential Buildings in South Korea. *Buildings* **2022**, *12*, 51. [CrossRef]
112. Turner, C.; Oyekan, J.; Stergioulas, L.K. Distributed Manufacturing: A New Digital Framework for Sustainable Modular Construction. *Sustainability* **2021**, *13*, 1515. [CrossRef]
113. Chang, Y.; Wilkinson, S.; Potangaroa, R.; Seville, E. Economics. Identifying factors affecting resource availability for post-disaster reconstruction: A case study in China. *Constr. Manag. Econ.* **2011**, *29*, 37–48. [CrossRef]
114. Rosni, N.A.; Noor, N.M. A Review of Literature on Urban Sprawl: Assessment of Factors and Causes. *J. Archit. Plan. Constr. Manag.* **2016**, *6*, 12–35.

115. Ankrah, N.A. Implementation of Cradle to Cradle diversity principles in business site development scheme. *Int. J. Urban Sustain. Dev.* **2018**, *10*, 92–108. [CrossRef]
116. Kucukvar, M. How Can Collaborative Circular Economy Practices in Modular Construction Help Fédération Internationale de Football Association World Cup Qatar 2022 to Achieve Its Quest for Sustainable Development and Ecological Systems? *Front. Sustain.* **2021**, *2*, 758174. [CrossRef]
117. Hamza, M. Exploring Perceptions of the Adoption of Prefabricated Construction Technology in Pakistan Using the Technology Ac-ceptance Model. *Sustainability* **2023**, *15*, 8281. [CrossRef]
118. Oorschot, J.A.; Halman, J.I.; Hofman, E. The adoption of green modular innovations in the Dutch housebuilding sector. *J. Clean. Prod.* **2021**, *319*, 128524. [CrossRef]
119. Kaminska, P.; Michalak, H. Innovative, modular building facades—As a tool to counteract the effects of and to prevent climate change. *Civ. Environ. Eng. Rep.* **2023**, *32*, 184–209. [CrossRef]
120. Ismail, F.; Haji, F.; Donyavi, S.; Boyd, P.; Sohrab, D. Climate change and the energy performance of buildings in the future—A case study for prefabricated buildings in the UK. *J. Build. Eng.* **2021**, *39*, 102285. [CrossRef]
121. Ghobadi, M.; Sepasgozar, S. Circular economy strategies in modern timber construction as a potential response to climate change. *J. Build. Eng.* **2023**, *77*, 107229. [CrossRef]
122. Alkhalidi, A.; Abuothman, A.; Aldweik, A.; Al-Baaz, A. Is it a possibility to achieve energy plus prefabricated building worldwide? *Int. J. Low-Carbon Technol.* **2021**, *16*, 220–228. [CrossRef]
123. Ahn, Y.; Kim, K. Sustainability in modular design and construction: A case study of 'the stack'. *Int. J. Sustain. Build. Technol. Urban Dev.* **2014**, *5*, 250–259. [CrossRef]
124. Juaristi, M.; Sebastiani, I.; Avesani, S. Timber-based façades with different connections and claddings: Assessing materials' reusability, water use and global warming potential. *J. Facade Des. Eng.* **2022**, *10*, 71–86. [CrossRef]
125. Balasbaneh, A.; Marsono, A. New residential construction building and composite post and beam structure toward global warming mitigation. *Environ. Prog. Sustain. Energy* **2018**, *37*, 1394–1402. [CrossRef]
126. Hao, J.; Cheng, B.; Lu, W.; Xu, J.; Wang, J.; Bu, W.; Guo, Z. Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. *Sci. Total Environ.* **2020**, *723*, 137870. [CrossRef]
127. Lees, E.; Eyre, N. Thirty years of climate mitigation: Lessons from the 1989 options appraisal for the UK. *Energy Effic.* **2021**, *14*, 37. [CrossRef] [PubMed]
128. Liu, C.; Zhang, F.; Zhang, H. Comparative analysis of off-site precast concrete and cast-in-place concrete in low-carbon built environment. *Fresenius Environ. Bull.* **2020**, *29*, 1804–1812.
129. Zhu, L.; Yang, Y.; Chen, S.; Sun, Y. Numerical study on the thermal performance of lightweight temporary building integrated with phase change materials. *Appl. Therm. Eng.* **2018**, *138*, 35–47. [CrossRef]
130. Kechidi, S.; Banks, N. Minimizing upfront carbon emissions of steel-framed modular housing: A case study. *J. Build. Eng.* **2023**, *72*, 106707. [CrossRef]
131. Rockwood, D.; Silva, J.; Olsen, S.; Robertson, I.; Tran, T. Design and prototyping of a FRCC modular and climate responsive affordable housing system for underserved people in the pacific island nations. *J. Build. Eng.* **2015**, *4*, 268–282. [CrossRef]
132. Yevu, S.; Owusu, E.; Chan, A.; Sarpong, K. Systematic review on the integration of building information modelling and prefabrication construction for low-carbon building delivery. *Build. Res. Inf.* **2023**, *51*, 279–300. [CrossRef]
133. MacIvor, J.; Margolis, L.; Perotto, M.; Drake, J. Air temperature cooling by extensive green roofs in Toronto Canada. *Ecol. Eng.* **2016**, *95*, 36–42. [CrossRef]
134. Iommi, M. The mediterranean smart adaptive wall. An experimental design of a smart and adaptive facade module for the mediterranean climate. *Energy Build.* **2018**, *158*, 1450–1460. [CrossRef]
135. Labrecque, N.; Oudjene, S.M.M.; Blanchet, P. Finite element study of hyperstructure systems with modular light-frame construction in high-rise buildings. *Buildings* **2022**, *12*, 330. [CrossRef]
136. Wang, S. Analytical solutions for the dynamic analysis of a modular floating structure for urban expansion. *Ocean. Eng.* **2022**, *266*, 112878. [CrossRef]
137. Han, Q.; Chang, J.; Liu, G.; Zhang, H. The carbon emission assessment of a building with different prefabrication rates in the construction stage. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2366. [CrossRef] [PubMed]
138. Ceranic, B.; Beardmore, J.; Cox, A. Rapid deployment modular building solutions and climatic adaptability: Case based study of a novel approach to "thermal capacity on demand". *Energy Build.* **2018**, *167*, 124–135. [CrossRef]
139. Luo, L.; Chen, Y. Carbon emission energy management analysis of LCA-based fabricated building construction. *Sustain. Comput. Inform. Syst.* **2020**, *27*, 100405. [CrossRef]
140. Messana, J.; Lopez, V.; Pellicer, T. City regeneration through modular phase change materials (PCM) envelopes for climate neutral buildings. *Sustainability* **2022**, *14*, 8902. [CrossRef]
141. Carranza, A.; Anon-Abajas, R.; Lamela, G. A research methodology for mitigating climate change in the restoration of buildings: Rehabilitation strategies and low-impact prefabrication in the "El Rodezno" water mill. *Sustainability* **2021**, *13*, 8869. [CrossRef]
142. Shen, J.; Copertaro, B.; Zhang, X.; Koke, J. Exploring the potential of climate-adaptive container building design under future climates scenarios in three different climate zones. *Sustainability* **2020**, *12*, 108. [CrossRef]

143. Gan, V. BIM-based building geometric modeling and automatic generative design for sustainable off-site construction. *J. Constr. Eng. Manag.* **2022**, *148*, 04022111. [CrossRef]
144. Maodus, N.; Agarski, B.; Budak, I.; Radeka, M. Life cycle and energy performance assessment of three wall types in south-eastern Europe region. *Energy Build.* **2016**, *133*, 605–614. [CrossRef]