Article

Integrating Circular Economy Principles in Modular Construction to Enhance Sustainability

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Abstract: Modular construction (MC) has gained attention due to its potential for fast construction, reduced construction waste, and lower environmental impact while having several other issues on stimulating sustainability. The circular economy (CE) focuses on better resource management through a closed-loop system. Even though MC enhances sustainable practice, several pitfalls barricade sustainability in MC (high initial investment, design consideration, and technology challenges). Nevertheless, the synergy between CE and MC has not been investigated in past studies to address the issues in MC to achieve sustainability. This study investigates the integration of CE principles in MC to enhance sustainability. This study used a qualitative approach via the Delphi technique by conducting three semi-structured expert interview rounds with the use of a purposive sampling method. The collected data were analysed using manual content analysis. This study identified nine notable issues in MC to achieve sustainability, and all CE 9-R (rethink, refuse, reduce, reuse, repair, refurbish, remanufacture, recycle, and recover) principles could address those identified issues. Accordingly, thirty implementation strategies were recognised to fill the gap between the problems in MC and the potential of CE principles to solve the issues. The results provide insights for construction practitioners, policymakers, and researchers on integrating CE principles into MC processes to achieve sustainability goals. Ultimately, this study highlights the significance of a holistic approach by theoretically combining MC and CE principles as a benchmark for future studies. As a contribution, CE strives to make the planet a safe place to live by combatting resource depletion.

Keywords: circular economy (CE); modular construction (MC); sustainability; 9-R principles; integration

1. Introduction

The circular economy (CE) concept is aimed at changing present consumption and output patterns that considerably strain the Earth’s ability to cope with environmental challenges [1]. This is widely explored worldwide to replace the traditional economic framework of “take, make, and dispose of” and solve resource efficiency and environmental issues [2]. The core notion of a CE is to replace the concept of end-of-life. Further, the CE is an industrial and economical approach for restoration and regeneration [3]. The CE aims for the construction industry to eliminate or reduce waste [4], increase building use, and facilitate resource improvement [5]. The 3-R (reduce, reuse, and recycle) principles were identified as the significant principles leading to a CE in the beginning [6]. In addition, it then increased to 9-R, which the 11-R have now replaced (rethink, redesign, repair, refurbish, remanufacture, reuse, recycle, recover, reduce, regenerate, responsible) technique [7]. Recently authors have identified that R principles can enhance sustainability in the built environment [8]. In addition, Ref. [9] revealed that the CE is commonly used to realise sustainability, focusing more on the social, economic, and environmental aspects. The CE paradigm gives a lot of context and impetus for the building industry to achieve sustainability [10]. The principles of the circular economy play a pivotal role in pursuing...
sustainability. This economic model emphasises the design of products for durability and reuse, maximising resource efficiency, and implementing effective recycling and waste management practices. By adopting these principles, industries and societies can minimise waste, optimise resource utilisation, and contribute to a more sustainable future.

Modular construction (MC) is a sustainable construction method that can assist in achieving cost-effectiveness [11]. MC is regarded as one of the most sustainable construction methods due to its waste-free design feature, detaching construction lifecycles from finite material usage [12]. MC offers notable contributions to sustainability. Modular construction minimises material waste and reduces environmental impact through its offsite manufacturing process. Furthermore, the modular approach enables easy disassembly and reconfiguration [13]. MC is a game-changing technology because it provides faster construction, safer manufacturing, better quality control, reduced construction time by 50% and cost by 20%, and lower environmental impacts than traditional on-site construction [14].

Despite the sustainability benefits of modular construction (MC), there remain issues that hinder its full potential [15], such as project planning, communication and coordination, site constraints [16], transportation of modules, the initial cost of the production plant, resistance to change [17], and resource depletion [14]. However, scholars have suggested that integrating CE principles can address these sustainability issues. Numerous past studies have investigated the MC concept, its new advancements, challenges, opportunities [13,15], and sustainability issues [10]. Furthermore, previous studies have investigated combining CE and sustainability [18,19]. Nevertheless, a few studies have been conducted on the synergy between CE, MC, and sustainability [18]. Henceforth, this study aimed at in-depth investigations on integrating CE principles in MC to enhance sustainability with its practical implementation. A comprehensive study is conducted to fulfil the above-identified industrial need and the existing literature gap addressing the below research questions:

1. What are the notable issues in MC in achieving sustainability?
2. What are the applicable CE principles to overcome the above-identified notable issues in MC?
3. What are the strategies to avoid notable issues of MC in achieving sustainability?
4. What strategies could assist in integrating CE principles in MC to achieve sustainability?

This study adopted the following pathway to address the above aim:

Firstly, Section 2 (Literature Review) has determined the importance of integrating CE principles for stimulating MC’s sustainability. Secondly, Section 3 (Methodology) phase-wise presents the adopted research methodology in all three Delphi rounds, and Section 4 presents the research findings. Thirdly, under Section 5 (Discussion) the findings and results of this study is interpreted, analysed, and connected to existing literature to provide a comprehensive understanding of integrating CE principles to achieve sustainability in MC. Lastly, Section 6 offers the implications of theory and practice, followed by the conclusions.

This study demonstrates that the challenges associated with achieving sustainability in MC can be effectively addressed by incorporating CE principles. Identifying implementation strategies that facilitate the integration of MC with CE principles is of particular importance. This integration expands the existing theoretical discourse and advances the comprehension of the tangible ramifications of sustainable construction practices. Moreover, this study offers valuable insights to practitioners who aim to adopt modular construction techniques efficiently and socially responsibly. Ultimately, it makes a noteworthy contribution to improving society.

2. Literature Review

2.1. Applicability of Modular Construction to Stimulate Sustainability

The term “modular construction” comes from industrial design, which describes breaking down a whole product into several modular parts based on various functional assessments within a given range [13]. MC is a cutting-edge construction method using the mass manufacture of industrialised systems [19]. Further, MC is a creative and environmentally friendly construction technique that maintains a prominent trend in architecture
and engineering [20]. Consequently, recent technological advancements offer the intriguing potential for increased modularisation in more extensive and complicated projects with urbanisation [21]. The whole structure of a modular building consists of modules, which are manufactured and moved from a factory offsite [22]. The benefits of using MC over traditional construction relate to the decrease in material waste [20], improved safety [23], reduced building construction time [13], improved quality [24], cost reduction [14], reduced environmental impact, and lower weight [25]. MC delivers less maintenance, higher quality, and a more durable modular structure [26]. MC requires less energy throughout its lifespan, including the extraction, production, transport, and construction phases [27]. Therefore, MC receives more and more attention, and prefabricated components are created considerably more rapidly and effectively; the overall length of a project duration can be shortened [28].

Development that satisfies present needs without jeopardising future generations’ capacity is called sustainability [29]. Some effects of the current global energy crisis include the gradual degradation of the global ecology and the depletion of fossil fuel supplies; the over usage of traditional energy sources is the leading cause [30]. The idea of sustainability is wanted for increasingly crucial scientific research on environmental problems, environmental management strategies, and industrial and agricultural output, among other things [31]. Sustainability is significant in ensuring societal stability and economic success for future generations [32]. The integration of sustainability principles with MC offers significant potential for reducing the environmental impact of the building process. Significantly, over a 50-year life cycle of building (excluding replacement), MC lowered energy consumption by 4.6% and greenhouse gas emissions by 3% [25]. With this, the sustainability performance growth of MC has become increasingly popular [33]. Through the controlled factory setting, MC allows for precise material planning and minimised waste generation [19]. This results in optimised resource utilisation and reduced material wastage compared to traditional construction methods. The standardised nature of modular components facilitates the incorporation of energy-efficient technologies, including insulation systems and energy-saving appliances, leading to reduced energy consumption throughout the building’s lifecycle [29]. By utilising sustainable materials and incorporating renewable energy technologies, MC has contributed to a more environmentally conscious and resource-efficient approach to building. The sustainable construction industry is thought to have a bright future because of MC [34]. Economic success, environmental quality, and social equality must all be prioritised simultaneously to be sustainable [35]. Sustainable construction should follow this triple bottom line [36]. Sustainable definitions hold up well to the finished MC performance, and the construction process’s sustainability is improved by MC [37].

2.2. Issues in Modular Construction to Achieve Sustainability

Examining MC’s social, economic, and environmental impacts disclosed several difficulties in sustainably executing MC [12]. Therefore, it is necessary to address the main reported issues with project planning, structural response or performance, fire and energy performance, transportation difficulty, higher initial investment and cost, reliable connection systems, lifting limits of tower cranes, lightweight and high-performance materials, and lack of access during renovations [37]. Effective project planning and scheduling are paramount as they optimise resource utilisation, minimise waste, and reduce environmental impact. Efficient scheduling enables streamlined processes, reducing material requirements and improving overall sustainability [38]. Additionally, structural response or performance, fire and energy performance, and reliable connection systems must be carefully considered during the design and construction phases to ensure that modular buildings meet rigorous sustainability standards [31]. Transport difficulties and the necessity of larger vehicles during handling and installation pose challenges to sustainability due to increased energy consumption and emissions [23,39].
Modules also require significant design work to guarantee that structural and architectural integrity is preserved during these operations, which cause excessive resource consumption that barricades sustainable practices [37]. The noise levels of MC prefabrication facilities are higher than during on-site building and project planning [40]. Moreover, quality control systems are imperative for sustainable MC. Rigorous quality control measures during manufacturing and assembly help address issues such as module damage, insufficient manufacturing capacity, and excessive material requirements [36]. In addition, inadequate manufacturing capacity spends considerable time fulfilling the market demand which can affect project details as a direct or indirect consequence [41]. Furthermore, modular units are typically transported from the factory to the construction site for final assembly. This transportation phase often requires specialized vehicles and equipment capable of carrying large and bulky modules [42]. The need for larger vehicles for transportation can contribute to increased material usage, such as fuels, tires, and other resources associated with vehicle maintenance. Additionally, the installation of modular units at the construction site may require the use of supplementary materials to facilitate connections and ensure structural integrity. These materials may include fasteners, adhesives, seals, or insulation to join modules together and create a unified and robust structure [43].

However, a comprehensive and systematic approach is required to address the interconnected challenges in MC and enhance sustainability. Through optimised resource utilisation, reduced waste generation, improved energy efficiency, and the promotion of durable and environmentally friendly construction practices, MC can emerge as a sustainable solution for the built environment. Table 1 illustrates the MC issues for achieving sustainability identified by past studies.

<table>
<thead>
<tr>
<th>MC Issue for Achieving Sustainability</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Project planning and scheduling</td>
<td>[44–49]</td>
</tr>
<tr>
<td>2 Structural response or performance</td>
<td>[44,46,50,51]</td>
</tr>
<tr>
<td>3 Fire and energy performance</td>
<td>[46,50,52,53]</td>
</tr>
<tr>
<td>4 Transport difficulties</td>
<td>[44,54–57]</td>
</tr>
<tr>
<td>5 High initial investment</td>
<td>[16,37,54,57,58]</td>
</tr>
<tr>
<td>6 Cost reliable connection systems</td>
<td>[48,50,55,59]</td>
</tr>
<tr>
<td>7 Need more materials for transporting, handling, and installation</td>
<td>[37,46,52,52,57]</td>
</tr>
<tr>
<td>8 Design consideration</td>
<td>[37,47,50,57,60]</td>
</tr>
<tr>
<td>9 Factory coordination</td>
<td>[46,54]</td>
</tr>
<tr>
<td>10 Skilled labour</td>
<td>[46,52,56,58]</td>
</tr>
<tr>
<td>11 Factory noise level</td>
<td>[37,49,54,61]</td>
</tr>
<tr>
<td>12 Higher construction cost</td>
<td>[52,56]</td>
</tr>
<tr>
<td>13 Aesthetic appearance</td>
<td>[45,50,54,56,59,62]</td>
</tr>
<tr>
<td>14 Need large vehicles for handling and installation</td>
<td>[37,47,57,63]</td>
</tr>
<tr>
<td>15 Extensive coordination and communiation</td>
<td>[47,50,51,55,62,64]</td>
</tr>
<tr>
<td>16 Internal design of modules</td>
<td>[44,60,63]</td>
</tr>
<tr>
<td>17 Insufficient quality control systems</td>
<td>[47,54,57]</td>
</tr>
<tr>
<td>18 Technology challenges</td>
<td>[37,49,58]</td>
</tr>
<tr>
<td>19 Restricted flexibility</td>
<td>[49,52,59,60,65]</td>
</tr>
<tr>
<td>20 Modular parts getting damaged during installation</td>
<td>[44,50,54,59,60]</td>
</tr>
<tr>
<td>21 Inadequate manufacturing capacity for modular units</td>
<td>[49,55,58,64]</td>
</tr>
<tr>
<td>22 More material requirement</td>
<td>[45,47,50,55,59,60,66]</td>
</tr>
</tbody>
</table>
The identified issues from the past studies will change with external factors (e.g., environmental, financial, and organisational). A sustainable approach to MC can improve this technology’s environmental and social impact and unlock its full potential as a cost-effective and efficient construction method. Therefore, it is crucial to prioritise sustainability in MC to ensure its long-term success and relevance in the industry.

2.3. Why Is It Important to Integrate Circular Economy Principles to Overcome Issues in Modular Construction to Achieve Sustainability?

People’s increased consumption led to increased trash, which impacts all aspects of the environment, including global warming and contaminating the land, oceans, and rivers [67]. As per [68], the combination of competing nations’ economic growth and the population’s constant rise in living standards while using finite natural resources constitutes one of the twenty-first century’s significant problems without jeopardising global environmental stability. The construction industry has been known to consume a significant amount of natural resources in the past three decades; it was in charge of over 40% in the 1990s and accounts for about 32% today [69]. The construction industry is one of the biggest producers of waste and pollution when considering the complete life cycle of a building [70]. The construction sector is recognised as the greatest challenge to sustainable development because it uses 40% of the world’s energy and emits 33% of the CO$_2$ [71]. Thus, the construction industry receives the most attention during the CE transition because of its enormous resource consumption [72].

The primary goal of the CE concept is to delinearise the connection between environmental impact and economic expansion [73]. By incorporating CE principles into the construction industry, numerous opportunities occur to reduce energy consumption, greenhouse gas emissions, and waste creation [74], boosting productivity in the construction industry [75]. Due to its industrial design and predetermined capabilities for disassembly and reuse, the modular structure has great potential to serve as a starting point for this transformation [18]. MC has long been viewed as the way to increase the construction industry’s productivity due to its ability to harness industrial processes’ effectiveness [39,46,76]. By employing this technique, more than 75% of the building process is finished offsite, resulting in financial and environmental savings [77]. However, several issues, such as high initial cost, design limitations, technology challenges, inadequate manufacturing capacity, and supply chain issues, have hindered the widespread adoption of MC. Integrating CE principles such as reducing waste, reusing and recycling materials, and designing for circularity help address these issues [37]. For instance, MC facilitates the reuse of building components. When a modular building reaches the end of its useful life, its modules can be disassembled and refurbished. Components in good condition can be reused directly in new projects, reducing the demand for new materials. Any materials that cannot be reused can be recycled, further minimising waste [52]. Further, traditional construction methods generate significant amounts of waste, including excess materials and unused resources. With MC, the controlled manufacturing environment and precise planning result in reduced waste generation during the construction process [47]. The off-site manufacturing process allows for precise measurement and planning, reducing material waste. Moreover, modular buildings are often designed to be disassembled and reconfigured, enabling the reuse of modules in different projects, thus extending their lifespan [44].

The linkage between MC and CE manifests in their inherent alignment despite being distinct concepts. MC, characterised by the use of prefabricated modules assembled off-site, enhances construction efficiency and precision. CE, on the other hand, seeks to establish a sustainable economic model by minimising waste and maximising resource utilisation. By applying these principles, MC can become more efficient, cost-effective, and environmentally friendly, leading to greater sustainability. Recently, the CE idea has generated more interest from various industries at various levels, and incorporating a CE into MC can facilitate the successful transition to sustainable construction [68].
Nevertheless, a substantial gap exists in the literature and industrial practice on clearly identifying issues for achieving sustainability in MC and addressing such issues through CE principles. According to previous studies, issues with project planning and scheduling, structural responses, fire and energy performances, high initial investments, high construction cost, extensive coordination and communication, and difficulties in quality control \[12,37,45,46\], have been identified as significant issues in MC for achieving sustainability. Therefore, the methodology has been designed to collect relevant data for addressing that research problem by integrating CE principles.

3. Methodology

This study’s main aim is to perform an in-depth analysis of integrating CE principles in MC to achieve sustainability. Firstly, a comprehensive literature review was conducted following a sequential process. Initially, a meticulous definition of the research topic was established, accompanied by the formulation of specific research questions to identify the central concepts and themes relevant to this study. Subsequently, an exhaustive compilation of keywords and phrases was generated, encompassing direct terms and synonymous expressions and variations.

As this study is not a systematic literature review, the identification of key literature was undertaken to ascertain the research gap. The first step for identifying the research gap consisted in determining the search engines, appropriate keywords, and the time span. Accordingly, the literature review used search engines such as Google Scholar, Web of Science, Scopus and ScienceDirect, which are renowned as large repositories of different studies. With this, articles were extracted from major publishers such as Elsevier, Emerald, Springer, Taylor & Francis, and Wiley. To refine and combine keywords to obtain more targeted and relevant results Boolean operators were used as logical connectors to create complex search queries and specify relationships between different concepts \[78\] such as AND, OR, and NOT. The search string included the keyword “construction industry” connected with “sustainability”, “CE”, and “MC”. Finally, the retrieved articles were rigorously evaluated, encompassing the examination of abstracts or full texts, which informs iterative adjustments to the search strategy, facilitating the construction of a comprehensive and focused area in CE, MC, and sustainability \[78\]. Then, as the first screening, each paper’s title and abstract were examined by evaluating their relevance based on the inclusion criteria. The articles based on irrelevant subject areas such as supply chain management, building information modelling (BIM), virtual reality (VR), and other industries (e.g., manufactory industry and services) were excluded. Further, review articles were excluded to avoid any probable bias to define the research gap. The article search was initiated in January 2022 and was continued till May 2022.

The qualitative approach enables the researcher to assess beliefs and actions and make new connections \[79\]. Since the concept of CE is novel to the construction industry, industry practitioners’ perception has to be investigated to derive a concise output. Thus, this study follows sequential philosophical thinking using a qualitative research design. With the expectation of achieving a consensus for the literature findings, the Delphi technique is the most suitable qualitative data collection technique for conducting multiple iterations from selected experts \[80\].

This study used the Delphi technique to explore the research area in-depth by gathering and synthesising expert opinions \[81\]. Engaging a panel of experts facilitated the generation of comprehensive insights and diverse perspectives. Three rounds of Delphi interviews enhanced the findings’ reliability and validity \[82\]. After each round, the researcher summarises the results of prior rounds while omitting their names to obtain expert consensus \[81\]. According to \[82\], the primary goals of the many rounds are to achieve consensus by reducing response variation and enhance precision through controlled feedback and repetition. A study \[83\] emphasises that a consensus will be reached in social science studies after two to three Delphi rounds. Thus, a three-round Delphi technique
was conducted to achieve the study objectives. Accordingly, data saturation was reached without adding any new content by three rounds.

Further, the number of rounds was stipulated with the accommodated time and resource constraints. Delphi surveys typically employ a consistent group of experts across all rounds [82]. However, the number of experts participating in the survey was progressively reduced in rounds 01, 02, and 03 due to time and resource limitations. It was difficult to occupy all experts for all three rounds due to the high engagement of experts in the industry/academia. Previously, [82,84] found that factors meeting or exceeding a selection rate of 75% were deemed significant, and this was consequently designated as the cut-off point. Thus, a 75% agreement rate was considered as the cut-off point in this study. The Delphi process spanned from August 2022 to January 2023, encompassing a defined timeframe for data collection and iterative consensus-building among expert participants.

3.1. Data Analysis

Content analysis is one of the most used methods for analysing qualitative data [85,86]. According to S. L. Bengtsson (2022) [87], content analysis helps to categorise data by minimising the collected data and boosting the contextual meaning. It has a few specific criteria to follow [88]. The method used for coding, a crucial data analysis stage, depends on the study’s breadth, time, and financial limitations [89]. Manual content analysis allows researchers to gain a comprehensive and nuanced understanding of the data [90]. By manually examining the content, researchers can delve into the details, identify subtle patterns, and capture context-specific information that the automated or quantitative methods may have missed [91]. Thus, manual content analysis was used to analyse the qualitative findings of the survey, which enabled the researcher to focus on human coding and accurately boost the contextual meaning of findings [87,92].

3.2. Delphi Round I

Delphi Round I consisted of two (02) phases, and the interview questions were divided into those two phases accordingly. The main objective of Round I was to confirm and modify the literature findings for the following two phases:

Phase 01: Identifying the notable issues in MC in achieving sustainability.
Phase 02: Identifying the CE principles to achieve sustainability in MC.

Next, the gathered data were analysed and refined for Delphi Round II phase 01 for confirmation by Round II.

Notably, the objectives of each phase of the three Delphi rounds were formed according to the research objectives/research questions. For instance, after finishing Delphi Round I, a part of the first research question was fulfilled while it extended to Delphi Round 2.

3.3. Delphi Round II

The results’ confirmation by Round I experts was further investigated during Round II. Significantly, the results from Round I Phase 02 and Round II Phase 01 were integrated to ascertain the applicable circular economy principles to overcome each notable sustainability issue for MC. Accordingly, the primary purpose of Round II was to ascertain the CE principles applicable to address notable sustainability issues for MC in the general context, as presented in the below phases.

Phase 01: Investigating the notable sustainability issues in MC, which can be solved using CE principles.
Phase 02: Identifying the implementation strategies of the CE principles to achieve sustainability in MC.

Afterward, the data were analysed and refined for Delphi Round III Phase 01. The first research question was fully addressed at the end of Delphi Round II. The second and third research questions were partially addressed.
3.4. Delphi Round III

Results confirmed by experts from Round II were used to clarify Round III specifically for each notable sustainability issue. Then, the applicable CE principles were presented for each issue, and suitable implementation strategies were proposed before relevant CE principles. The two (02) phases are as follows:

Phase 01: Investigating suitable CE principles to overcome notable sustainability issues in MC.

Phase 02: Proposing the implementation strategies to integrate CE principles to overcome notable sustainability issues in MC.

With this, the second and third objectives were fully addressed as an extension of the Delphi Round II findings. Finally, the Delphi Round III findings answered the fourth research question.

3.5. Delphi Expert Selection

In Delphi Round interviews, the expert selection criteria are crucial since they are used to select the most appropriate interviewers for the study [58,60]. Qualitative researchers use the purposive sampling technique to identify individuals who can offer in-depth and comprehensive details about the subject under research [93–95]. Therefore, all experts were selected using purposive sampling with a carefully designed list of criteria to occupy experts with practical experience in the industry and theoretical knowledge in the research areas. The criteria were executed to select an appropriate sample [96]. Thus, respondents were filtered according to the compulsory and additional qualifications revealed in Table 1. Accordingly, experts with academic and industry experiences were chosen as respondents to this study. Even though the criteria specified two years of professional experience, only three respondents have less than five years of experience in the construction industry. Except for those three respondents, all other experts have more than five years of experience (in the construction industry). Nevertheless, those three respondents are core researchers in CE, MC, and sustainability areas. Thus, all thirteen respondents are professionally qualified as per the given criteria for this study.

Further, heterogeneous purposive sampling, which allows for collecting data that can ensure maximum variation within the sample in different settings, contexts, countries, and backgrounds, was used to select the survey respondents [59,62,63]. As stated by [97], ten to twenty experts should contribute in the first round to generate a solid result from a Delphi survey. Figure 1 illustrates the flowchart of the research process followed.

In this study, the population was selected based on the criteria given in Table 2. Accordingly, thirteen respondents were interviewed in Round I, whereas eleven participated in Round II. Round III of the survey consisted of ten respondents. Table 2 presents the experts’ profiles.
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Figure 1. Flow chart for the research process.
Table 2. Expert Selection Criteria and Profiles.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Compulsory Qualifications</th>
<th>Additional Qualifications (Satisfy at Least Three)</th>
<th>Code</th>
<th>Delphi Round 1</th>
<th>Delphi Round 2</th>
<th>Delphi Round 3</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Industry</td>
<td>At Least Two Years Working Experience</td>
<td>At Least Two Years of Industry/Research Experience (Satisfy at Least Two)</td>
<td>E1</td>
<td></td>
<td></td>
<td></td>
<td>PhD Candidate</td>
</tr>
<tr>
<td>Circular Built Environment Practice</td>
<td>At Least Five Years of Construction Organization Experience in a Related Area</td>
<td>Having a Construction-Related Degree</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
<td>General Manager</td>
</tr>
<tr>
<td>Modular Construction Practice</td>
<td>At Least Two Years of Research in a Related Area</td>
<td>Having Reading a Construction-Related Post Graduate Degree</td>
<td>E3</td>
<td></td>
<td></td>
<td></td>
<td>Chartered Quantity Surveyor</td>
</tr>
<tr>
<td>Sustainability Practice</td>
<td>Professional Experience (Satisfy at Least Two)</td>
<td>Interest and Knowledge in Circular Economy and Modular Construction</td>
<td>E4</td>
<td></td>
<td></td>
<td></td>
<td>Managing Director</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accessibility</td>
<td>E5</td>
<td></td>
<td></td>
<td></td>
<td>Senior Lecturer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Code</td>
<td>E6</td>
<td></td>
<td></td>
<td></td>
<td>Assistant Professor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E1</td>
<td>E7</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>E8</td>
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<tr>
<td></td>
<td></td>
<td>E3</td>
<td>E9</td>
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<td></td>
<td></td>
<td>E4</td>
<td>E10</td>
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<td></td>
<td></td>
<td>E5</td>
<td>E11</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>E6</td>
<td>E12</td>
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<td></td>
<td></td>
<td>E7</td>
<td>E13</td>
<td></td>
<td></td>
<td></td>
<td>Construction Manager</td>
</tr>
</tbody>
</table>
4. Findings

The findings of this study are presented under four sub-sections; notable issues in MC in achieving sustainability, suitable CE principles to overcome each notable sustainability issue in MC, implementation strategies to integrate CE principles to overcome each notable sustainability issue in MC, and framework for integration of CE principles in MC to enhance sustainability.

4.1. Notable Issues in MC for Achieving Sustainability

The findings from Round I Phase 01 and Round II Phase 02 are presented in this section. At the end of the literature review, twenty-two issues were identified as sustainability issues when implementing MC (refer to Table 1).

According to the expert interviews (Round I Phase 01), the respondents accepted three issues from the literature, amalgamated four issues into one issue, four issues into two issues, and one issue was modified, as demonstrated with the “*” mark (e.g., * Extensive factory coordination and communication). Moreover, experts proposed two new issues to the list, depicted in “bold” marks (e.g., High-risk involvement). Thus, nineteen issues were identified as issues in MC for achieving sustainability after the end of Round I Phase 01.

In Round II Phase 02, ten issues were omitted due to the lack of 75% (cut-off) of experts’ responses, depicted in the “grey” highlight (e.g., Skilled Labour). After Delphi Round II Phase 01, nine notable issues were identified in MC for achieving sustainability, as illustrated in Table 3.

Table 3. Notable MC Issues for achieving Sustainability.

<table>
<thead>
<tr>
<th>Issue Code</th>
<th>MC Issues for Sustainability</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>E7</th>
<th>E8</th>
<th>E9</th>
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<td>I19</td>
<td>More material requirement</td>
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</table>
Regarding the need for more materials and large vehicles for transporting, handling, and installing, modular parts getting damaged during installation. E1 stated that:

[...] “There could be time lags and much expense when the modules are transported from one country to another”. E4 and E6 agreed.

With this, E2 mentioned frequent delays in getting permission to cross bridges, sharp turns, traffic jams, crane setup, or temporary roads. Thus, all respondents confirmed the transportation difficulty as a major issue.

The high initial investment is a significant issue in the MC industry. E3 noted that “at the beginning of MC, there is more money to build the offsite plant or factory from the contractor’s perspective”. This investment is typically required to build an offsite plant or factory to manufacture the modules, which can be costly. By reusing and refurbishing materials, companies can reduce their material and production costs, which helps offset the initial investment required. Similarly, the design consideration has been identified as an issue, and E4 emphasised that modules are manufactured in a plant, completed in the proper shape, and internal and external designs are limited to change. E5 and E8 also confirmed the issue of customising module sizes according to space or financial requirements. This issue can be addressed by encouraging design for deconstruction, which allows for easy disassembly and reuse of modular components. E1, E2, E3, E4, E5, E8, E9, E19, and E11 agreed with this “restricted flexibility” in design.

The extensive factory coordination and communication are identified as issues since MC stimulates offsite construction. E10 stated that “In most cases, the factory workers/designers are not well aware of the actual site layout, and sometimes, details related to space availability in the actual construction site are not communicated to relevant parties at the factory. With this, issues arise during installation, where it can generate unnecessary waste that barricades sustainable practise”.

Improper project planning and scheduling is a derived notable issue where this is a root cause for other issues such as quality of the output, cost efficiency, risk in timely completion, and so on. E12 stated that the high initial cost of MC can be mitigated through proper project planning and scheduling as it stimulates timely completion.

E2, E5, E6, and E10 suggested “high-risk involvement” as an issue with safety aspects. E5 suggested that companies can reduce their risk and improve safety by using recycled or repurposed materials that are safe and durable. By incorporating CE principles into their operations, companies can ensure that they take a sustainable and responsible approach to MC while also realising the potential cost and efficiency benefits of MC technology. Consequently, respondents highlighted the lack of suppliers as an issue to MC and to make the maximum financial and quality benefits from MC. E2 emphasised,

[...] “Maintaining an MC plant in their site is not beneficial financially until this technology is accepted by consumers at large”.

Thus, contractors and customers cannot obtain a competitive advantage in price and quality with few suppliers.

4.2. Suitable CE Principles to Overcome Each Notable Sustainability Issue in MC

The findings from Round I Phase 02 and Round III Phase 01 are presented in this section. The literature findings indicated that 9-R CE principles could overcome the MC issues for sustainability. In Round I Phase 02, the respondents suggested all 9-R CE principles to mitigate/avoid issues in MC. Those findings were supported to address the second research question “What are the applicable CE principles to overcome the above-identified notable issues in MC?”. Consequently, all CE R principles were brought to Delphi Round III. With this, in Round III Phase 01, experts were expected to categorise each CE R principle that could appear in front of each notable issue, which was finalised in Delphi Round II Phase 01. Before the interview, the experts were presented with the list of nine CE R principles and identified nine notable issues for achieving sustainability in MC. The CE principles with over 75% (cut-off) agreement per principle were considered applicable for that particular issue. Thus, at the end of Delphi Round III Phase 01, the
second research question had been fully addressed. Accordingly, Table 4 illustrates the applicable CE principles to overcome notable issues for achieving sustainability in MC.

Table 4. Suitable CE Principles to Overcome Notable Issues for Achieving Sustainability in MC.

<table>
<thead>
<tr>
<th>MC Issues for Sustainability</th>
<th>Suitable CE Principle</th>
<th>No. of Responses</th>
<th>MC Issues for Sustainability</th>
<th>Suitable CE Principle</th>
<th>No. of Responses</th>
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<td>R0- Refuse</td>
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<td>R7- Repurpose</td>
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</table>

Common R principle for all notable issues, and unique R principles for specific notable issues.

According to E5, “The meaning of the refuse in MC is rejecting design or project concept”. Moreover, E1 highlighted that lightweight and cost-effective materials could be used instead of large extensive materials by refusing. Hence, wanted and unwanted items should be decided at the beginning of the project. The “rethink” principle was confirmed as a common principle for all the notable issues. E9 stated that “Product or purpose (modular units and parts) can be innovatively and intensely by using the rethink concept”. According to the expert opinions, “rethink” was the main principle considered at the beginning of the issue, and that is the linking principle with other principles. According to E5,

[...] “There could be additional material wastage for transporting and handling because rethink, repair, and recover of materials is significant to achieve sustainability in MC”.

While the “remanufacture” principle was established only for the high initial investment and extensive factory coordination and communication because remanufacture initiates additional costs for the project. Subsequently, the “recover” principle was suggested only for needing more materials and large vehicles for transporting, handling, and installing; also, when modular parts get damaged during installation and design consideration.
E3 emphasised that if the project design is complicated and unsuitable for the intended purpose, it should be adjusted through rethinking and/or repurposing. For the technology challenge, E4 suggested checking the technology for the MC context and rethinking other technologies which can act as alternatives to gain the same or enhanced outcome. The availability of suppliers is also a barrier to attaining sustainability in MC while it restricts sustainable project delivery. Thus, E4 emphasised the possibility of repairing, reusing, and refurbishing modules. With this, E7 emphasised that

[...]” Repairing, reusing and refurbishing promote sustainable consumption patterns, extend the lifespan of modules, minimise the need for new production, reduce landfill waste, conserve energy and raw materials, and contribute to the CE by keeping valuable resources in use for longer periods”. E1, E3, and E9 confirmed this finding.

Table 4 indicates the common R principles for all the notable issues in MC in achieving sustainability in “yellow”. In contrast, unique R principles for specific notable issues are illustrated in “green”.

4.3. Implementation Strategies to Integrate CE Principles to Overcome Each Notable Sustainability Issue in MC

The findings from Round II Phase 01 and Round III Phase 02 are presented in this section. The experts were given a list of twenty implementation strategies based on literature findings at the beginning of Round II Phase 02 to practice CE principles that are maintained, deleted, or merged with others during the filtering process. With this, experts accepted ten implementation strategies from the literature with no change. Five implementation strategies were modified, and four implementation strategies were amalgamated into two implementation strategies. The experts proposed 13 new implementation strategies. Finally, 30 implementation strategies were determined for executing CE principles. With this, the third research question was answered by revealing the strategies to avoid notable issues of MC in achieving sustainability.

In Round III Phase 02, the experts defined the implementation strategies to address each notable MC issue to enhance sustainability by integrating CE principles. Experts in Round III confirmed all-new implementation strategies identified in Delphi Round II. Minimising or eliminating the need for new construction materials by reducing space and multi-functional was typical for all notable issues. The above and the other five implementation strategies were confirmed as common implementation strategies for more than seven issues, and implementing a risk assessment was the unique implementation strategy. Significantly, 17 strategies were allocated for over 50% of identified notable issues. After the CE principles were categorised in a specific notable issue, the experts were requested to categorise the implementation strategies to achieve sustainability in MC by the given list finalised during Delphi Round II Phase 01 (refer to Table 2).

The need for large vehicles and machinery to transport and install modules is a major issue for MC to achieve sustainability. Accordingly, E1 stated that

[...] “Deconstruction designs can be identified and implemented within the MC; then modular parts can be used for other new MC projects; however, if that deconstruction project location should be near the new project, then this issue can be avoided”.

E3 and E9 stated that some large modules could be divided into smaller units without altering the employer’s requirements concerning their experience. Regarding the high initial investment, E9 suggested prioritising local, renewable, biodegradable, and recyclable materials for MC. Similarly, E11 stated that

[...] “Circularity requires that materials be reused in the market, such as through material banks, and that a digital platform is developed for users to reuse and resell the products”, where it supports getting the maximum benefit of the initial investment. Further, experts have highlighted the use of new technologies, including BIM, 3D printing, and Artificial Intelligence (AI), to avoid the design challenges of MC.
Regarding manufacturing capacity, the experts highlighted process automation which shortens lead time and boosts module production. When considering the availability of suppliers as an issue, E4 stated that “[…] “MC businesses might work with suppliers to guarantee that circular materials are easily accessible and a consistent supply. By doing this, capacity limitations may be avoided. An adequate supply of raw materials for manufacture may be guaranteed”.

Accordingly, as the development of answers to the third research question, the strategies to assist in integrating CE principles in MC to achieve sustainability were found at the end of Delphi Round III Phase 02.

As illustrated in Table 5, thirty implementation strategies were finalised to avoid notable MC issues in achieving sustainability using CE principles. Figure 2 briefly maps the outcomes of this study with notable issues for achieving sustainability in MC, CE 9-R principles to avoid those notable issues, and relevant implementation strategies.

Table 5. Implementation Strategies.

<table>
<thead>
<tr>
<th>S1</th>
<th>Minimise or eliminate the need for new construction materials by reducing space and multi-functional use</th>
<th>S11</th>
<th>Match supply and demand</th>
<th>S21</th>
<th>Substitute fossil fuel-intensive materials with bio-based materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>Policies for resource reduction</td>
<td>S12</td>
<td>Restore assets or parts to be reused and parts to be reinstalled in the entity</td>
<td>S22</td>
<td>Use abandoned buildings for other purposes</td>
</tr>
<tr>
<td>S3</td>
<td>Repair defective assets</td>
<td>S13</td>
<td>Stimulate the use of recyclable and organic materials</td>
<td>S23</td>
<td>Divide the overall modular units into small modular units</td>
</tr>
<tr>
<td>S4</td>
<td>Develop low-material and energy solutions</td>
<td>S14</td>
<td>Consider environmentally significant materials without hazardous materials</td>
<td>S24</td>
<td>Substitute non-renewable energy supply with purchased or produced renewable energy</td>
</tr>
<tr>
<td>S5</td>
<td>Design for deconstruction</td>
<td>S15</td>
<td>Increase the materials’ durability and quality for longer life spans</td>
<td>S25</td>
<td>Innovative materials with discarded parts, components etc., for different purposes</td>
</tr>
<tr>
<td>S6</td>
<td>Couple end of life to a new life cycle</td>
<td>S16</td>
<td>Smart design for efficient maintenance application</td>
<td>S26</td>
<td>Consider environmental impact scenarios in design selection</td>
</tr>
<tr>
<td>S7</td>
<td>Re-evaluate and reuse the necessary assets, elements, and components</td>
<td>S17</td>
<td>Stimulate separability on the material level</td>
<td>S27</td>
<td>Substitute new materials with used materials whenever possible</td>
</tr>
<tr>
<td>S8</td>
<td>Increase adaptability</td>
<td>S18</td>
<td>Use new technology, such as construction and manufacturing process automation, RFID, RFID, BIM, IoT, AI, and 3D printing</td>
<td>S28</td>
<td>Use discarded components, parts, etc., to produce new versions to use for the same purpose</td>
</tr>
<tr>
<td>S90</td>
<td>Product as a service from product sale</td>
<td>S19</td>
<td>Implement a risk assessment</td>
<td>S29</td>
<td>Loose-fit design, cold-formed structure design freezing concept can be used</td>
</tr>
<tr>
<td>S10</td>
<td>Use recycled materials and resources from other waste</td>
<td>S20</td>
<td>Use and promote the material</td>
<td>S30</td>
<td>Eliminate the use of unnecessary elements, components, materials, etc.</td>
</tr>
</tbody>
</table>

Common strategies; Unique strategies; at least common for 50% of issues.
Figure 2. Framework for Integration of CE Principles in MC to Enhance Sustainability.

S1, S3, S4, S5, S7, S10, S11, S13, S14, S16, S17, S20, S23, S27, S28, S30

R0, R1, R2, R3, R4, R5, R6, R7, R8

S1, S3, S4, S5, S6, S7, S13, S15, S16, S17, S18, S21, S24, S25, S26, S27, S29

R0, R1, R2, R3, R7

S1, S3, S4, S5, S6, S7, S9, S10, S11, S13, S15, S18, S20, S23, S26, S27

R0, R1, R2, R4, R7, R8

S1, S2, S4, S5, S6, S7, S8, S11, S14, S15, S16, S17, S24, S25, S28, S29, S30

R1, R2, R3, R4, R7

S1, S2, S5, S7, S9, S14, S15, S16, S19, S20, S21, S23, S24, S25, S26, S27

R0, R1, R2, R3, R4, R5, R7
A holistic view of MC integration with CE principles shows proper strategies will prevent most issues. Additionally, implementing one strategy would mitigate or avoid other MC issues to achieve sustainability.

4.4. Framework for Integration of CE Principles in MC to Enhance Sustainability

Figure 2 demonstrates a summary of the integration of CE principles for MC by addressing issues in MC to achieve sustainability. The framework has been derived from the findings presented under Section 4.1 (Notable Sustainable Issues in MC for Achieving Sustainability), Section 4.2 (Suitable CE Principles for Achieving Sustainability in MC), and Section 4.3 (Implementation Strategies to Integrate CE Principles to Overcome Each Notable Sustainability Issue in MC). In the framework, one (common) strategy for all the issues is indicated in “brown”, one unique strategy is illustrated in “green”, and strategies applicable to at least 50% of issues are shown in “blue”. Further, the framework (Figure 2) needs to be referenced to Table 5 which includes implementation strategies presented under Section 4.3.; the specific strategies are denoted by codes (i.e., S1, S2, S3, S4 . . .). For instance, R0 to R9 CE principles can be applied through S1, S3, S4, S6, S7, S8, S9, S11, S13, S15, S17, S20, S22, S23, S24, S25, S27, S28, and S30 to address the issue of high initial investment. Moreover, a comprehensive and systematic approach is required to address the interconnected challenges in MC and enhance sustainability. Through optimised resource utilisation, reduced waste generation, improved energy efficiency, and the promotion of durable and environmentally friendly construction practices, MC can emerge as a sustainable solution for the built environment. Subsequently, these integrated findings were effectively aligned with implementation strategies, which were thoughtfully and comprehensively outlined in a coherent manner at the culmination of the analysis in the presented framework. The presented framework serves as a comprehensive guide, enabling readers to effectively discern the correlation between notable sustainability issues in MC, the corresponding CE 9-R principles that can be employed to tackle those issues, and the specific strategies for implementing these principles. By consolidating this information in a single location, the framework facilitates a clear understanding of the interplay between sustainability challenges, CE principles, and their practical application.

5. Discussion

The discussion section consists of four sub-sections; notable issues in MC in achieving sustainability, CE principles to achieve sustainability in MC, implementation strategies to integrate CE principles to overcome notable sustainability issues in MC, and framework for integration of CE principles in MC to enhance sustainability.

5.1. Notable Issues in Modular Construction in Achieving Sustainability

The use of MC affords sustainable production in many ways and can be considered a cross between manufacturing and construction [62]. Literature findings revealed 22 issues. During the interview, the experts accepted nine notable issues as amalgamations, modifications, and additions to previous issues. All experts accepted large vehicles and machinery requirements to transport, handle, and install as significant issues to reach sustainability in MC because of the high fuel consumption, carbon emissions and inefficiency, time consumption, and unnecessary waste generation [39]. Refs. [37,44] emphasised that carbon emissions and waste generation have a direct connection as a barrier to achieving sustainability in MC. The literature revealed that high initial investment in MC has created a negative perception of return on investment among employers [10,38].

Thus, even though E1 emphasised that the initial investment is high, the interview findings supported that structures can be created offsite in a controlled environment within half the time of conventional construction—providing long-term benefits. The high initial investment has been identified as a major issue in MC, and the authors suggested that the positive or negative effects of the investment should be determined after a cost–benefit
analysis where it accounts for social benefits. Ref. [61] also supported the idea that MC gains long-term benefits, regarding social benefits.

The literature has separately identified design considerations and technology challenges [50,51]. However, E3 added a contrasting idea stating that early design consideration cannot be changed within the construction period, but technological tools, including modern visualisation techniques, would make it possible. E7 and E8 stated that already designed modules enhance sustainability within the manufacturing process as a contract fact for the literature findings. Proper planning and scheduling are also identified as an issue in achieving sustainability in MC [49]. Even though MC has numerous issues in achieving sustainability, many interviewees expressed that these issues would be mitigated or resolved with the integration of CE principles.

5.2. Circular Economy Principles to Achieve Sustainability in Modular Construction

This study identified that all 9-R CE principles are convenient to mitigate the notable issues in MC to achieve sustainability. Respondents suggested refusing as a potential CE principle to avoid all eight issues except the availability of suppliers. More than half of the respondents confirmed that “refuse” emphasises the importance of making conscious choices to reduce waste and prevent generating materials that may become burdensome throughout their lifecycle [37]. For instance, high-risk involvement can be mitigated at the initial stage by refusing high-risk involved activities.

On the contrary, E8 suggested “replace” as a CE principle, but other experts argued that this principle is covered under refurbish, remanufacture, and repurpose principles. Nevertheless, E7 suggested that substituting unsustainable or resource-intensive products, materials, or processes with more sustainable alternatives will avoid issues in transportation and manufacturing capacity. This principle focuses on identifying and implementing innovative solutions that minimise environmental impact and resource depletion [46]. Thus, E6, E8, and E10 supported this fact by stating that replacing inefficient or harmful practices with more sustainable options and the circular economy aims to promote the use of renewable resources, reduce waste generation, and enhance overall environmental sustainability.

Significantly, “rethink” was suggested for all the notable issues where it avoids the starting point of the problem. “Refusing” is considered replacing a product with similar or superior features and fewer negative impacts while depreciating one with adverse effects [25]. In connection with design considerations and technology challenges, “rethink” has sufficient potential to mitigate the issues in MC to achieve sustainability. Subsequently, respondents suggested “recover” and “remanufacture” for only a few issues. “Recover” reduces the need for extracting new raw materials and minimises waste generation, contributing to a more sustainable and resource-efficient economy that emphasises the linear model of CE [70].

Further, the process of restoring used products or components to a new condition, often with added improvements or upgrades, is defined as “remanufacture” [68]. As demonstrated by the respondents, “remanufacture” focuses on extending the life cycle of products through repair, refurbishment, and reassembly, allowing them to be reintroduced into the market, where it creates the same meaning that emerged from the literature. Thus, remanufacturing reduces the demand for new production, conserves resources, and promotes circularity by keeping products in circulation for as long as possible.

The experts further emphasised that “CE principles are mostly related to materials in the construction industry”. On the other hand, identified issues emerged due to the lags and laps with the logistic process, material consumption, manufacturing capacity, project planning, scheduling, etc. Thus, CE principles advocate convenient but straightforward procedures to avoid those issues. For instance, E9 suggested that

[... “Existing modular parts can be used for new modular building; then it can prevent requirements of large modular elements from the material ‘reusing’ with less transportation difficulty”.

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Hence, implementing relevant CE principles should be clearly defined to maximise MC–CE integration.

5.3. Implementation Strategies to Integrate Circular Economy Principles to Overcome Notable Sustainability Issues in Modular Construction

This study identified strategies to overcome each notable issue in MC for sustainability by applying CE principles. The literature findings identified 20 generic implementation strategies used to practice CE. Experts were asked to use these implementation strategies with some modifications for notable MC issues. With this, experts have accepted 10 implementation strategies from the literature. Five implementation strategies were modified, and four implementation strategies were amalgamated into two implementation strategies. The experts proposed 13 new implementation strategies.

As per the findings, issues on transporting, handling, and installation of modules can be addressed through “refuse”, “rethink”, “reduce”, and “reuse”. Hence, these CE principles can be executed with the multi-functional use of materials. Further, separability that stimulates the efficiency of the transportation process will solve this issue [78].

Streamlining the MC process with new technology can decrease a project’s time and labour requirements [18]. For instance, the speedy and precise creation of modular components is possible with 3D printing technology [57]. Lowering lead times and boosting construction efficiency leads to prompt delivery [98]. E5 further supported this as “New technology can assist in lowering the likelihood of mistakes or flaws. By doing this, the construction project’s overall quality can be increased with rework”. All interviewers opined that those issues could be avoided in design consideration, factory coordination and communication, project planning, and scheduling through new technologies. For instance, “rethink” and “repurpose” find new and alternative uses for products, materials, or components that have reached the end of their original intended life cycle. Instead of disposing of these items as waste, repurposing aims to give them a new purpose or function [74]. As suggested by experts, this can be practically implemented by matching supply and demand and substituting new materials that can be reused. Furthermore, lifecycle risk assessment was identified as a strategy to minimise the high risk involved in the literature. E10 supported this and said, “Modular component lifecycle risk assessments can be used to find possible hazards and problem areas”.

At a glance, using defined CE principles through suggested implementation strategies will avoid nine notable issues. Significantly, an implementation strategy will be supported to solve one or more issues simultaneously.

5.4. Framework for Integration of CE Principles in MC to Enhance Sustainability

Effective project planning and scheduling are paramount as they optimise resource utilisation, minimise waste, and reduce environmental impact. Efficient scheduling enables streamlined processes, reducing material requirements, and improving overall sustainability [38]. Additionally, structural response or performance, fire and energy performance, and reliable connection systems must be carefully considered during the design and construction phases to ensure that modular buildings meet rigorous sustainability standards [31]. The expert opinions also aligned with this fact by emphasising the fact of reducing waste generation through a properly outlined planning process. Transport difficulties and the necessity of larger vehicles during handling and installation pose challenges to sustainability due to increased energy consumption and emissions [23, 39]. However, few experts suggested the repair of defective assets and reuse of modules as a strategy to address those issues where it was mentioned in the previous literature.

Modules also require significant design work to guarantee that structural and architectural integrity is preserved during these operations, which causes excessive resource consumption and barricades sustainable practices [37]. Nevertheless, restoring assets, reuse of parts, and use of recyclable materials make designs work smoothly. The noise levels of MC prefabrication facilities are higher than during on-site building and project plan-
Rigorous quality control measures during manufacturing and assembly help address issues such as module damage, insufficient manufacturing capacity, and excessive material requirements [36]. In addition, inadequate manufacturing capacity spends considerable time to fulfill the market demand which can affect project details as a direct or indirect consequence [41]. Furthermore, modular units are typically transported from the factory to the construction site for final assembly. This transportation phase often requires specialised vehicles and equipment capable of carrying large and bulky modules [42]. The need for larger vehicles for transportation can contribute to increased material usage, such as fuels, tires, and other resources associated with vehicle maintenance. Additionally, the installation of modular units at the construction site may require the use of supplementary materials to facilitate connections and ensure structural integrity. These materials may include fasteners, adhesives, seals, or insulation to join modules together and create a unified and robust structure [43].

In summary, the findings from the conducted interviews were compared to the existing literature through pattern matching, leading to the finalisation of integrated findings to present the framework that illustrates the integration between notable issues of MC to achieve sustainability, suitable CE principles to address those issues, and implementation strategies to integrate CE principles with MC notable issues to achieve sustainability.

6. Conclusions

In conclusion, this study addressed sustainability issues in modular construction (MC) by integrating circular economy (CE) principles. A literature review and three-round Delphi surveys identified twenty-two issues, which were reduced to nine notable issues, including high cost, inadequate manufacturing capacity, and technology challenges. Experts accepted the applicability of all nine CE principles to address these notable issues in MC for achieving sustainability.

In Delphi Round III Phase 01, experts separately categorised each CE principle that could address the identified issues. Throughout this study, a minimum response rate of 75% was deemed critical to upholding the study’s rigour and credibility. The experts also defined 30 implementation strategies to mitigate or avoid notable sustainability issues in MC by integrating CE principles. Different strategies were proposed for each notable issue, including re-evaluating the necessity of assets, restoring assets or parts to be reused and reinstalled, using new technologies, dividing overall modular units into small modular units, and more. This study addressed the gap in integrating CE principles in MC for practical implementation from a sustainability perspective. Hence, it is imperative to integrate CE principles and meticulously implement the proposed strategies to effectively address the notable sustainability issues in MC, including but not limited to high cost, inadequate manufacturing capacity, and technological challenges.

6.1. Theoretical Contribution

The present study prominently contributes to theory by identifying the issues in MC for achieving sustainability, even though MC is a construction innovation for stimulating sustainability. Moreover, the significance of CE principles is identified beyond their typical application by synthesising the concepts of sustainability and CE in a novel and innovative manner. This integration extends the theoretical discourse and enhances the understanding of the practical implications of sustainable construction practices.

6.2. Practical Contribution

This study provides valuable insights for practitioners seeking to adopt MC techniques effectively. The integration of circularity in MC stimulates innovation and the development of sustainable business models. It encourages collaboration across the value chain, including manufacturers, designers, contractors, and stakeholders, to find novel solutions that minimise waste, optimise resource use, and create economic opportunities.
6.3. Contribution to the Society

The integration of CE principles with MC brings significant contributions to society. This approach reduces environmental impacts by minimising resource consumption, waste generation, and carbon emissions. It also offers economic benefits through cost savings, job creation, and the development of sustainable industries. Ultimately, circularity in MC promotes long-term sustainability, fostering a resilient built environment that meets the needs of present and future generations. With this, CE strives to make the planet a safe place to live by combatting resource depletion.

The intervention of CE principles provided a potential solution to those issues in a limited scope. The study’s findings cannot be generalised to all contexts where their technological, financial, organisational, and environmental factors differ. In terms of future research directions, construction automation’s role in enhancing sustainability in MC can be investigated through the basis created via CE principles. Instead of MC, integrating CE principles for waste and supply chain management would potentially obtain successful outcomes. Furthermore, these study findings are expected to serve as a benchmark for future research in providing valuable insights and laying the foundation for further inquiry in this area.


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