

Article

Synergising Circular Economy Principles in Industrialised Construction: Fuzzy Synthetic Evaluation of Key Constructs of Design for Circular Manufacturing and Assembly (DfCMA)

Kaveesha Gihani Dewagoda ^{1,*} , Ji Chen ¹, Mohan M. Kumaraswamy ^{1,2}  and S. Thomas Ng ³

¹ Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong; jichen@hku.hk (J.C.); mohan@hku.hk (M.M.K.)

² Department of Building Economics, The University of Moratuwa, Moratuwa 10400, Sri Lanka

³ Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong; thomasng@cityu.edu.hk

* Correspondence: kaveesha.gihani.dewagoda@gmail.com or kaveesha@connect.hku.hk

Abstract

Rapid urbanisation and population growth call for more Industrialised Construction (IC) as a swifter, safer, higher-quality and affordable means of delivering housing and infrastructure. Meanwhile, rising global temperatures and extreme weather patterns call for immediate action to combat environmental degradation. The Building Construction Industry (BCI) is a leading contributor to global resource extraction and waste generation, posing a significant threat to our environment and planet. Design for Circular Manufacturing and Assembly (DfCMA) is an overarching design framework that synergises circularity (Design for Circularity (DfC)) and modularity (Design for Manufacturing and Assembly (DfMA)) by enhancing their shared values. This study explores the functional apparatus of DfCMA by identifying 21 DfMA constructs and 20 DfC constructs in the BCI through a rigorous literature review, first analysed descriptively, followed by Exploratory Factor Analysis (EFA) and Fuzzy Synthetic Evaluation (FSE) of the initial findings from a suitably focused questionnaire survey. The study findings confirm the significance of applying the 41 constructs above in advancing the concept of DfCMA in the BCI. This study thus adds value to research and practice, exploring the underlying mechanism of this novel DfCMA concept, which synergises two imperatives, promoting a Circular Economy (CE) and DfMA principles and practices in IC.



Academic Editor: Ahmed Senouci

Received: 28 July 2025

Revised: 1 September 2025

Accepted: 5 September 2025

Published: 8 September 2025

Citation: Dewagoda, K.G.; Chen, J.; Kumaraswamy, M.M.; Ng, S.T. Synergising Circular Economy Principles in Industrialised Construction: Fuzzy Synthetic Evaluation of Key Constructs of Design for Circular Manufacturing and Assembly (DfCMA). *Buildings* **2025**, *15*, 3239. <https://doi.org/10.3390/buildings15173239>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: Design for Circular Manufacturing and Assembly (DfCMA); Design for Circularity (DfC); Design for Manufacturing and Assembly (DfMA); Building Construction Industry (BCI); Industrialised Construction (IC); Circular Economy (CE); Whole Life Cycle (WLC); Construction Value Chain (CVC)

1. Introduction

The Building Construction Industry (BCI) is responsible for 33.5% of the total waste generated globally [1]. A total of 40% of annual material extraction in the BCI is lost during the End of Life (EoL) of buildings, which accounts for approximately one-fourth of the total waste generated in the European Union [2,3]. The waste generated during building demolition is almost eight times that of the Construction Waste (CW) generated during the Beginning of Life (BoL) of buildings [4]. Since only a small fraction of Construction and Demolition Waste (CDW) can be and is diverted, most of it ends up in landfills, which

negatively impacts the surrounding air quality due to dust and harmful gas emissions, pollutes water resources by contamination with toxic materials, and ultimately degrades the health and well-being of communities and adversely affects land development [5]. CDW landfilling is conspicuous in rapidly growing economies; for example, CDW accounts for 25% of the total landfilling in Hong Kong [6]. This amounts to a grave concern given its space limitation for urbanisation [7].

Policy plays a pivotal role in CDW Management (CDWM) by implementing stringent regulations to minimise CDW generation [4], such as levying penalties on unauthorised landfilling or illegal dumping [5]. Hence, policy formulation and implementation that focus not only on EoL CDW efficiency but also on CDW effectiveness at the BoL through design optimisation are gaining traction [8]. Mesa et al. [9] advocate for preventive sustainability at the BoL over reactive sustainability at the EoL by designing out waste, as the design phase has the highest potential of determining the CDWM of a product across its Whole Life Cycle (WLC). However, CDW remains a challenge, particularly in developing countries, since the Circular Economy (CE) concept promotes eco-effectiveness over eco-efficiency through design at the BoL of a building [10]. Indeed, it is observed that the CE evolved recently as a paradigm of CDWM. For example, the ‘waste hierarchy’ of CDWM prioritises waste prevention over waste reuse, recycling, recovery and disposal [4], which forms the basis of CE principles in the BCI. Considering the intense environmental impact of CDW and landfilling, CE adoption is promoted as the new future of the BCI [11].

However, CE is to be practised not only as a CDWM or design strategy but also as a business strategy to recover and valorise CDW [12]. For this purpose, it is necessary to treat ‘Buildings as Material Banks’ (BAMB) [13] because, ultimately, valorisation of CDW depends on consumers’ perceived value [5]. For example, Marsh et al. [14] highlight how cement kiln dust, fines from natural coarse aggregate production, and concrete slurry waste could be valorised in the cement and concrete industries. Within the BCI, CE has strong inter-relationships with landfill diversion through reusing, remanufacturing, and recycling CDW, tracking and tracing resource streams, local material sourcing and passive building design strategies [15]. A CE in the BCI can be introduced as an economy in loops to reduce, recover and reuse CDW and extend the usable building life [16]. For example, rapidly growing economies such as Hong Kong are promoting CE strategies to address their CDWM challenges [7].

Hence, CDWM could be refined to apply combinations of CE strategies such as reuse, recycle, remanufacture, and recovery across the WLC of a building [17]. However, a CE should ideally aim to recognise and adopt the “optimal level of material loop closure to minimise the extraction of non-renewable virgin raw materials” [8] (pg. 1). In other words, it is critical to have a holistic understanding of the WLC of a building to select between different CE strategies to implement the optimal loop closure, taking the trade-offs into account [18]. Therefore, the entire Construction Value Chain (CVC) of a building, including circularity of energy sources, supply chains and business models, must be taken into account when adopting a CE in the BCI [11]. Hence, the CE approach for BCI takes a holistic overview of the CVC of a building ‘Designed for Circularity’ (DfC) [19,20], considering the WLC of a building to optimise its useful life, incorporating the EoL during the design stage, and using new ownership models [21]. Another prevalent solution to reduce CDW generation is prefabrication [22] wherein the platonic ideal is that prefabrication reduces CW generation up to 0% [5]. Under optimal circumstances, prefabrication can reduce CW generation in a factory setting by up to 5% with opportunities for recycling [23] and up to about 35% on site [24]. On the other hand, Kamali and Hewage [25] state that Industrialised Construction (IC) can reduce CW up to 25% given controlled administration in a factory setting. Kyrö et al. [26] support the notion and further reinforce the sustainability of IC not

only through a reduction in CW, but also by reducing carbon emissions, and enhancing quality, energy efficiency and the safety of workers.

Design for Manufacturing and Assembly (DfMA) is a design approach increasingly considered in IC that supports sustainability by reducing CEs, carbon emissions, and increasing circularity by promoting Design for Deconstruction (DfD) [27]. DfMA focuses on designing buildings for the ‘ease of manufacturing’ and ‘ease of assembly’ and does not necessarily relate to IC [22]. However, DfMA has wider applications in IC [24,28] that can minimise design variations and enhance overall productivity of the project when applied at the early design stages via stakeholder collaboration [29]. The primary objectives of DfMA application in the BCI, specifically in IC, are to enable a holistic approach to building design, encompassing both manufacturing and assembly, to provide an evaluation basis for production efficiency of IC, and to embrace modern methods of construction such as modular construction and prefabrication [30]. Yet, DfMA contributes to CW elimination in a controlled environment through precision, and returns “would-be waste back into the production process”, promoting circularity [31] (pg. 13). Regardless of the benefits of DfMA in IC, its applications are currently limited [29]; yet, there is a growing trend and interest in DfMA-oriented design of modular buildings [32].

It is thus established that DfC and DfMA in the BCI have a commonality through CW reduction, which is reinforced through ‘lean principles’. Benachio et al. [33] introduce Lean Construction (LC) as an approach to design and construct buildings to minimise waste and maximise value. Waste reduction is a core principle of LC, which further strengthens the link between DfC and DfMA. Since IC makes use of DfMA principles such as standardisation and error-proof design, CE principles such as reuse can be aligned to channel minimised CW to valorisation pathways [34]. In other words, both DfC and DfMA support ‘resource reduction’ by CW reduction through LC [16]. However, the explicit synergy of DfC and DfMA in IC at the intersection of CW reduction and LC is rarely explored [34]. For example, cities such as Hong Kong promote IC and CE to achieve the consolidated objectives of reducing the environmental footprint of buildings and enhancing the performance of construction projects [6]. Yet, the goals of CE, DfMA and LC are different. While LC aims to minimise CW and resource consumption in a production environment, DfMA seeks to improve the efficiency and productivity of manufacturing and assembly through design optimisation [31]. Meanwhile, CE in CI aims to narrow, slow and close resource loops by reducing resource input to the building, prolonging building life, and recovering and reusing resources for new purposes at their perceived EoL [16]. Yet, LC supports establishing a link between DfC and DfMA through its core principles, such as reducing non-value-adding activities, increasing process transparency, and process improvement with resource reprocessing, IC and modular construction [33].

According to the ‘value creation view’, IC is highly resource-efficient as it can deliver manufacturing-led high-value products [35]. Through a ‘value retention lens’, IC is highly resource efficient as it sustains the product value by facilitating high quality and design flexibility [35]. Hence, the authors recommended investigating the ecosystem of IC value chains to gain insights into the protracting resource efficiency of IC, including the resource effectiveness of the CE. Based on the speculations above, the authors of the paper above advanced the concept of Design for Circular Manufacturing and Assembly (DfCMA) in their previous publications [20,36]. The endeavour started by investigating CE adoption in the BCI through the theoretical lens of value and advanced DfC as a system thinking framework to create, develop and sustain circular value throughout the WLC of a building, where the ecosystem of stakeholders (circular value network) makes multi-criteria decisions to enable CE transition in the BCI [19,37,38]. Identifying the theoretical and industrial gap of synergising circularity and modularity in the BCI, the authors thus coined the term

DfCMA [20], which is “a design framework that facilitates both productivity and circularity by proposing ways to design a modular building that enables not only to be designed to be manufactured in a factory environment, minimising work on site, but also to narrow, slow and close resource loops based on circular value creation and retention across the whole building life cycle” [36] (pg. 3).

Even though the integration of a CE in IC is highly beneficial and unequivocal [34] through DfCMA, terms such as ‘circular IC’ or ‘circular modular buildings’ seldom appear in the literature [34,36]. Among the scarce literature, Kyrö, Jylhä and Peltokorpi [26] and Wuni and Shen [6] introduce ‘Circular modular construction projects’ as modular building projects that are designed, managed and constructed based on CE principles. In light of the above and the WLC stance of Pomponi and Moncaster [39] in defining a ‘circular building’, Dewagoda, Ng, Kumaraswamy and Chen [20] and Dewagoda, Kumaraswamy, Chen, Ng and Jayathunga [36] idealise the deliverable of DfCMA as a ‘circular modular building’, which is an optimised modular building that is designed, planned, constructed, used, and deconstructed across its WLC in a manner consistent with CE principles. However, the concept of DfCMA is yet to be established in the BCI. One step forward was to propose a DfCMA checklist for practitioners to optimally integrate CE principles in modular buildings [36]. Nevertheless, there is a lack of understanding of the constructs of DfCMA. Hence, this paper aims to identify the key constructs of DfC and DfMA that can be beneficially consolidated into DfCMA constructs to understand the underlying mechanism of DfCMA using the methods explained in Section 2. A questionnaire survey was used to collect the data. The results of the analysis, based on the questionnaire survey, are presented in Section 3. Section 4 compares the findings of this study with the extant literature. While Section 5 presents the limitations of the research methodology and results of this study, Section 6 concludes this study and makes recommendations for future research.

2. Methods

This study adopted a quantitative approach to propose the DfCMA constructs based on a positivist epistemology. Figure 1 illustrates the methodological framework used in this study.

This study combines the research methodology of Ekanayake et al. [40] and Ekanayake et al. [41], who successfully used a similar approach to evaluate vulnerabilities affecting the supply chain resilience of IC in Hong Kong, and adopts that of Wuni and Shen [6], who developed critical success factors for integrating CE into modular construction projects in Hong Kong. According to Figure 1, 5 basic steps were completed to develop key constructs of DfCMA:

1. Identification of constructs of DfMA and DfC through a vigorous and structured literature review.
2. Administration of the questionnaire survey and statistical pretesting of the collected data.
3. Descriptive analysis of DfMA constructs and DfC constructs.
4. Exploratory Factor Analysis (EFA) of DfCMA constructs.
5. Fuzzy Synthetic Evaluation (FSE) of DfCMA constructs.

The following sub-sections recount each of the steps of the research process in detail.

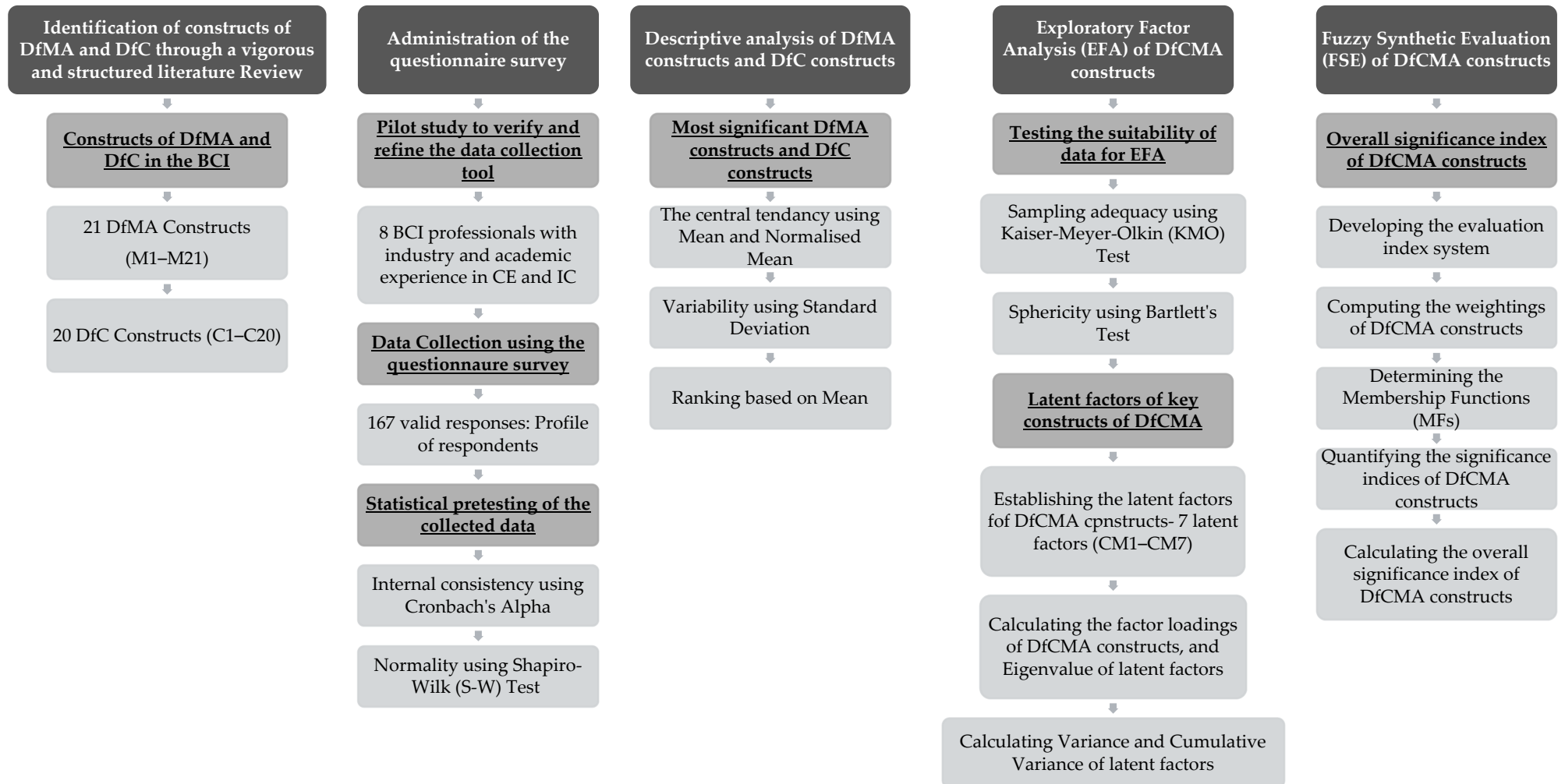


Figure 1. Methodological framework of research.

2.1. Identification of Constructs of DfMA and DfC by Reviewing the Extant Literature

A rigorous literature review was conducted to identify DfMA and DfC constructs in the BCI by identifying relevant research articles in commonly used databases such as Scopus, Web of Science and Google Scholar. In case the constructs were not BCI-specific, a further review was conducted to scientifically tailor them to befit the BCI, IC and modular buildings. Accordingly, 21 DfMA constructs and 20 DfC constructs specific to the BCI were identified in Section 3.1. These constructs were further analysed based on the literature, including the CVC stage in which the constructs transpire when applied during the design stage, as presented in Section 3.1.

2.2. Administration of the Questionnaire Survey and Statistical Pretesting of Data

A close-ended questionnaire survey was administered to evaluate the significance of the identified DfC and DfMA constructs based on a five-point Likert scale. The five points of the Likert scale were stated as follows: 1 (Very insignificant), 2 (Insignificant), 3 (Moderately significant), 4 (Significant), and 5 (Very significant). A pilot survey was carried out with 8 BCI professionals with industry and academic experience in either CE or IC or both to refine the structure of the questionnaire survey, remove ambiguous or less useful questions, and enhance the understandability [42]. In addition to inquiring about the clarity and flow of the questionnaire, the pilot survey participants were also asked about the readability of the online questionnaire developed using the ‘Qualtrics’ platform in both mobile and desktop devices. The questionnaire was also refined to simplify the highly technical terminology and reduce the time consumed in responding. The improved questionnaire was distributed globally through emails, social media platforms such as WhatsApp, and professional networking platforms such as LinkedIn. The targeted respondents were BCI professionals with experiential knowledge (academic or industry) or a deep understanding in at least one of the following categories or both:

1. CE and related concepts: CE, sustainability, circular building design, DfC, green construction, lifecycle carbon assessment of buildings, building retrofitting.
2. IC and related concepts: modular construction, IC, off-site construction, DfMA, LC, prefabrication, building fit-outs.

Accordingly, a total of 167 valid responses were received. Table 1 presents the profile of the respondents.

Table 1. Profile of respondents.

Category		Frequency (N = 167)	Percentage
Profession/Job Role	Engineer	74	44.3%
	Quantity Surveyor	41	24.6%
	Researcher/Academic	23	13.8%
	Construction Manager	11	6.6%
	Architect	8	4.8%
	Facility Manager	5	3.0%
	Material Supplier	1	0.6%
	Property Developer	1	0.6%
	PhD Student	1	0.6%
	BIM Coordinator	1	0.6%
	Material Supplier	1	0.6%

Table 1. Cont.

Category	Frequency (N = 167)	Percentage	
Discipline/ Area of Expertise	Civil Engineering	91	54.5%
	Quantity Surveying	47	28.1%
	Architecture	9	5.4%
	Construction/Project Management	8	4.8%
	Facilities Management	7	4.2%
	Environmental Engineering	5	3.0%
Organisation Type	Contractor	43	25.7%
	Public Entity	39	23.4%
	University	31	18.6%
	Consultant	31	18.6%
	Designer	7	4.2%
	Client	5	3.0%
	Independent (Researcher/Professional)	4	2.4%
	Property Developer	4	2.4%
	Maintenance Research and Development	1	0.6%
	Manufacturer	1	0.6%
	Material Supplier	1	0.6%
Industry/ Academic Experience (in years)	1–5	39	23.4%
	6–10	89	53.3%
	11–20	22	13.2%
	>20	17	10.2%
Engagement in CE and Related Concepts (in years)	No Experience	26	15.6%
	Less Than 1 Year	58	34.7%
	1–5	51	30.5%
	6–10	23	13.8%
	>10	9	5.4%
Engagement in IC and Related Concepts (in years)	No Experience	92	55.1%
	Less Than 1 Year	35	21.0%
	1–5	34	20.4%
	6–10	4	2.4%
	>10	2	1.2%
Region	Sri Lanka	79	47.3%
	Australia	25	15.0%
	United Arab Emirates	16	9.6%
	Hong Kong (S.A.R.)	13	7.8%
	United Kingdom	5	3.0%
	Qatar	4	2.4%
	New Zealand	4	2.4%
	Bahrain	2	1.2%
	Canada	2	1.2%
	Saudi Arabia	2	1.2%
	United States of America	2	1.2%
	Sweden	2	1.2%
	China	1	0.6%
	Ireland	1	0.6%
	Japan	1	0.6%
	South Africa	1	0.6%
	Unspecified	7	4.2%

The Statistical Package for Social Sciences version 30 by IBM (SPSS v.30) was used to manage and analyse the data collected through the questionnaire survey. Two statistical pretests were conducted to assess the internal consistency and normality of the dataset. The internal consistency was measured based on a 95% confidence level of Cronbach's Alpha ($\alpha = 0.05$). The dataset generated a Cronbach's Alpha value of 0.973 for 41 constructs (21 DfMA constructs and 20 DfC constructs), indicating excellent internal consistency of the dataset [43,44]. The Shapiro–Wilk (S-W) Test was used to measure the normality of the dataset [45]. According to the S-W test values stated under Section 3.2, the null hypothesis that 'the data is normally distributed' is rejected as the S-W test values of the constructs were lower than the standard statistical level of 0.05 ($p\text{-value} \leq \alpha = 0.05$) [46,47].

2.3. Descriptive Analysis of DfMA Constructs and DfC Constructs

Afterwards, the dataset was analysed descriptively using 'Mean', 'Normalised Mean', and 'Standard Deviation'. Equation (1) was used to calculate the Mean of each construct.

$$\text{Mean } \bar{x} = \frac{\sum_{i=1}^k (x_i \cdot f_i)}{N} \quad (1)$$

where x_i = Likert scale point value (1, 2, 3, 4, or 5); f_i = frequency of responses for each Likert point; k = number of Likert points ($k = 5$); N : total number of responses ($N = \sum f_i$)

The DfMA constructs and DfC constructs were ranked based on their Mean in terms of significance. Equation (2) was used to normalise the Mean of each construct using Min–Max normalisation.

$$\text{Normalised Mean} = \frac{\bar{x} - x_{\min}}{x_{\max} - x_{\min}} \quad (2)$$

where $\bar{x}$ = (Raw) Mean of each construct; $x_{\min}$ = Minimum possible value in the Likert scale ($x_{\min} = 1$); $x_{\max}$ = Maximum possible value in the Likert scale ($x_{\max} = 5$).

Following the work of Wuni and Shen [6], a Normalised Mean of a construct of 0.5 (based on a scale of 0 to 1) was considered the threshold to determine the significance of each construct. Equation (3) was used to calculate the Standard Deviation of each construct.

$$\text{Standard Deviation } \sigma = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N}} \quad (3)$$

where x_i = Likert scale point value (1, 2, 3, 4, or 5); $\bar{x}$ = (Raw) Mean of each construct; N : total number of responses ($N = \sum f_i$); f_i = frequency of responses for each Likert point.

The detailed descriptive analysis of DfMA and DfC constructs can be found in Section 3.2.

2.4. Exploratory Factor Analysis (EFA) of DfCMA Constructs

Exploratory Factor Analysis (EFA) was carried out following the descriptive analysis to understand the underlying structure of the latent causes of the DfCMA constructs. At the outset, the suitability of the dataset for EFA was analysed using the Kaiser–Meyer–Olkin (KMO) Test and Bartlett's Test [48]. Kaiser [49] introduces KMO as an index of factorial simplicity. In other words, KMO measures whether sufficient common variance exists within the dataset to be analysed using EFA. Bartlett's Test measures sphericity, that is, whether the correlation matrix of the dataset is an identity matrix [50].

Table 2 presents the results of KMO and Bartlett's tests for the EFA of DfCMA constructs.

Table 2. Results of KMO and Bartlett’s Tests of the dataset.

KMO	0.928
Bartlett’s Test	
Approx. Chi-Square	5306.176
df	820
Sig.	0.000 ($p < 0.001$)

According to Kaiser and Rice [51], a KMO of 0.7–0.9 is generally acceptable, and the dataset yielded an index of 0.933, which proves the significant suitability of the dataset for EFA. The result of Bartlett’s test of sphericity for the dataset is 5306.176 with a significance level of 0.000, which means that the constructs are significantly correlated. Based on the test result, EFA was carried out, and the results are presented in Section 3.3. To ensure the reliability and consistency of the EFA process, this study followed the recommendations of Howard [52]. ‘Principal component analysis’ was used as the factor analytic method, and ‘Kaiser criterion’ was the basis of factor retention. The EFA results were rotated using ‘Oblimin with Kaiser normalisation’ by way of oblique rotation in the SPSS software. The cut-off value for factor loadings was 0.4.

2.5. Fuzzy Synthetic Evaluation (FSE) of DfCMA Constructs

Fuzzy Synthetic Evaluation (FSE) has longstanding applications in the BCI [53,54] as a method to interpret uncertainties associated with complex decision-making related to sampling and analysis of datasets [55]. It has also been frequently used in the field of IC. For example, Ekanayake, Shen, Kumaraswamy and Owusu [40] employed FSE to evaluate vulnerabilities affecting the CVC resilience of IC in Hong Kong, whereas Hassan Ali et al. [56] made use of FSE to evaluate enablers influencing residential modular construction in developing countries. Similarly, FSE has wider applications in CE and surrounding concepts. Omer Mazen et al. [57] used FSE to analyse strategies to enhance CW recycling. FSE has applications in sustainable construction [58] and green construction [59] as well. Oluleye, Chan, Antwi-Afari and Olawumi [17] modelled principal success factors to achieve ‘Total Circularity’ in the BCI, while Ababio and Lu [60] modelled the determinants of circular procurement adoption in the BCI using FSE. Specifically, Wuni and Shen [6] developed critical success factors of integrating CE in IC projects in Hong Kong. Given the methodological structure and the proximity to this study, the processes followed in [6] were used in this study, following the steps stated below:

1. Developing the evaluation index system.
2. Computing the weightings of DfCMA constructs.
3. Determining the Membership Functions (MFs).
4. Quantifying the significance indices of DfCMA constructs.
5. Calculating the overall significance index of DfCMA constructs.

The following sub-sections detail each of the above steps.

2.5.1. Developing the Evaluation Index System

The first-level evaluation index system for the key constructs of DfCMA was defined as ‘U’. The second-level evaluation index system for the 07 latent factors (CM1–CM7) of key constructs of DfCMA was defined as follows:

$$U = (U_1, U_2, U_3, U_4, U_5, U_6, U_7)$$

where U_1 = CM1 design for sustainable and resilient building life cycle management.

U_2 = CM2 Design to facilitate lean building construction.

U_3 = CM3 Human-centred building design.

U_4 = CM4 Socio-technical design consideration of building systems.

U_5 = CM5 Design to achieve economies of scale in building manufacturing.

U_6 = CM6 Design for WLC resource sufficiency of the building.

U_7 = CM7 Design for productivity and efficiency in building construction and deconstruction.

The third-level evaluation index system for the DfCMA constructs within each latent factor group was defined as follows:

$$U_1 = (U_{11}, U_{12}, U_{13}, \dots, U_{1n})$$

$$U_2 = (U_{21}, U_{22}, U_{23}, \dots, U_{2n})$$

$$U_3 = (U_{31}, U_{32}, U_{33}, \dots, U_{3n})$$

$$U_4 = (U_{41}, U_{42}, U_{43}, \dots, U_{4n})$$

$$U_5 = (U_{51}, U_{52}, U_{53}, \dots, U_{5n})$$

$$U_6 = (U_{61}, U_{62}, U_{63}, \dots, U_{6n})$$

$$U_7 = (U_{71}, U_{72}, U_{73}, \dots, U_{7n})$$

where n = number of DfCMA constructs within each latent factor. For example, the third-level evaluation index system for CM1 is as follows:

$$U_1 = (U_{11}, U_{12}, U_{13}, \dots, U_{16})$$

where U_{11} = C5 adaptable spatial layouts; U_{12} = C4 flexible spatial layouts; U_{13} = C10 built-in serviceability of components and modules; U_{14} = C6 components that can be upgraded or modified; U_{15} = C8 use durable building materials; U_{16} = C7 reconfigurable spatial layouts and interchangeable components.

The rating scale used to evaluate the significance of DfCMA constructs was defined as follows:

$$V = \{1, 2, 3, 4, 5\}$$

where V_1 = Very insignificant; V_2 = Insignificant; V_3 = Moderately significant; V_4 = Significant; V_5 = Very significant.

2.5.2. Computing the Weightings of DfCMA Constructs

The weightings (W_s) of the DfCMA constructs were calculated objectively based on the empirical data from the questionnaire survey using the Normalised Mean method using Equation (4):

$$W_i = \frac{\mu_i}{\sum_{i=1}^5 \mu_i} \quad (4)$$

where i = a DfCMA construct (M1–M21, C1–C20) or a latent factor group (CM1–CM7); W_i = weighting of either individual DfCMA constructs or latent factor groups; μ_i = Mean of a DfCMA construct or Total Mean of a latent factor group. The following must be noted:

$$0 \leq W_i \leq 1 \text{ and } \sum(W_i) = 1$$

where $\sum(W_i)$ is the total of the weightings. A set of weights of DfCMA constructs within a latent factor group is defined as follows:

$$W_s = (W_1, W_2, W_3, \dots, W_n)$$

where W_s = set of weights of DfCMA constructs within a latent factor group; n = number of DfCMA constructs in a latent factor group.

2.5.3. Determining the Membership Functions (MF)

Triangular fuzzy numbers were used to determine the Membership Function (MF) following the work of Wuni and Shen [6], as it is a widely used approach in transforming Likert-scale responses into a fuzzy dataset. The MF of a DfCMA construct is calculated using Equation (5):

$$MF_{U_{in}} = \frac{X_{1U_{in}}}{v_1} + \frac{X_{2U_{in}}}{v_2} + \frac{X_{3U_{in}}}{v_3} + \frac{X_{4U_{in}}}{v_4} + \frac{X_{5U_{in}}}{v_5} \quad (5)$$

where $MF_{U_{in}}$ = MF of a DfCMA construct; U_{in} = a construct; $X_{jU_{in}}$ = percentage of Likert scale value the respondents assigned to a specific DfCMA construct; n = number of DfCMA constructs in a latent factor group; i = the latent factor group number; j = Likert scale point values. Therefore:

$$j = \{1, 2, 3, 4, 5\}$$

MF of a DfCMA construct is written as follows:

$$MF_{U_{in}} = (X_{1U_{in}}, X_{2U_{in}}, X_{3U_{in}}, X_{4U_{in}}, X_{5U_{in}})$$

Hence, the fuzzy matrix of DfCMA constructs in a latent factor group (CM1-CM7) can be denoted using Equation (6):

$$R_i = \begin{bmatrix} MF_{U_{i1}} \\ MF_{U_{i2}} \\ MF_{U_{i3}} \\ \dots \\ MF_{U_{in}} \end{bmatrix} = \begin{bmatrix} X_{1U_{i1}} & X_{2U_{i1}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \\ X_{1U_{i2}} & X_{2U_{i2}} & X_{3U_{i2}} & X_{4U_{i1}} & X_{5U_{i1}} \\ X_{1U_{i3}} & X_{2U_{i3}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \\ \dots & \dots & \dots & \dots & \dots \\ X_{1U_{in}} & X_{2U_{in}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \end{bmatrix} \quad (6)$$

where R_i = fuzzy matrix of DfCMA constructs in a latent factor group; $MF_{U_{in}}$ = MF of a DfCMA construct; U_{in} = a construct; $X_{jU_{in}}$ = percentage of Likert scale value the respondents assigned to a specific DfCMA construct. Accordingly, the MF of a latent factor group can be calculated using Equation (7):

$$D_i = W_s \cdot R_i \quad (7)$$

where D_i = MF of a latent factor group; W_s = set of weights of DfCMA constructs within a latent factor group; R_i = fuzzy matrix of DfCMA constructs in a latent factor group. Here, “ $\cdot$ ” is the fuzzy composite operation [6]. Since $W_s = (W_1, W_2, W_3, \dots, W_n)$, replacing R_i using Equation (6), the MF of a latent factor group (D_i) can be expressed using Equation (8):

$$D_i = (W_1, W_2, W_3, \dots, W_n) \cdot \begin{bmatrix} X_{1U_{i1}} & X_{2U_{i1}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \\ X_{1U_{i2}} & X_{2U_{i2}} & X_{3U_{i2}} & X_{4U_{i1}} & X_{5U_{i1}} \\ X_{1U_{i3}} & X_{2U_{i3}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \\ \dots & \dots & \dots & \dots & \dots \\ X_{1U_{in}} & X_{2U_{in}} & X_{3U_{i1}} & X_{4U_{i1}} & X_{5U_{i1}} \end{bmatrix} \quad (8)$$

According to Equation (8), the MF of a latent factor group (D_i) is defined as follows:

$$D_i = (d_{i1}, d_{i2}, d_{i3} \dots d_{in})$$

where D_i = MF of a latent factor group; D_{in} = degree of membership of the grade alternatives for a DfCMA construct.

2.5.4. Quantifying the Significance Indices of DfCMA Constructs

The significance index of a latent factor group is calculated using Equation (9):

$$S_{CMi} = \sum_{i=1}^n (D_i \times V_i) \quad (9)$$

Given that $D_i = (d_{i1}, d_{i2}, d_{i3} \dots d_{in})$ and $V = \{1, 2, 3, 4, 5\}$, Equation (9) can be elaborated as follows:

$$\begin{aligned} S_{CMi} &= \sum_{i=1}^n (D_i \times V_i) \\ S_{CMi} &= (d_{i1}, d_{i2}, d_{i3} \dots d_{in}) \times (V_1, V_2, V_3 \dots V_n) \\ S_{CMi} &= (d_{i1} * V_1) + (d_{i2} * V_2) + (d_{i3} * V_3) + (d_{i4} * V_4) + (d_{i5} * V_5) \end{aligned}$$

2.5.5. Calculating the Overall Significance Index of DfCMA Constructs

As the aggregation operator, the weighted average operator, which is widely used in mathematical modelling, was employed. Accordingly, the MF of the total dataset can be calculated using Equation (10) below:

$$D_{Overall} = W_{Overall} \cdot R_{Overall} \quad (10)$$

where $D_{Overall}$ = MF of the total dataset; $W_{Overall}$ = the weightings of latent factor groups (CM1–CM7); $R_{Overall}$ = fuzzy matrix of the total dataset.

Equation (10) is to be simplified in a similar approach to that of Equation (8) using fuzzy composite operation. Hence, the overall significance can be determined using Equation (11) below:

$$S_{Overall} = \sum_{i=1}^n (D_{Overall} \times V_i) \quad (11)$$

where $S_{Overall}$ = overall significance index of the dataset; $D_{Overall}$ = MF of the total dataset.

Here, $V = \{1, 2, 3, 4, 5\}$ and Equation (11) is to be simplified in a similar approach to that of Equation (10) to calculate the overall significance index. The results obtained using the methods above are presented in the next section.

3. Results

3.1. Constructs of DfMA and DfC in the BCI

Design for Manufacturing and Assembly (DfMA) is an overarching design framework originating in the manufacturing industry to improve product design and enhance production efficiency by considering downstream value chain activities of manufacturing and assembly [28,61]. In the BCI, DfMA has broader applicability in IC as a design strategy to improve time efficiency, economise building construction, enhance building quality and construction safety, reduce on-site labour and reduce re-work and CW [31]. The most common DfMA principles are reducing part count, repeating parts, standardisation, multi-functionality, flexible connections, modular design and design simplification [61–63]. Although many DfMA guidelines are available in the existing literature, careful consideration of the uniqueness of the BCI must be taken into account when translating these principles to the IC [63]. The same dilemma exists in translating the generic CE principles to the BCI [64]. For instance, the CVC in the BCI is highly fragmented [65]. Hence, the actors within the CVC interact discontinuously with each other, making the adoption of CE in the BCI complicated. Considering the drawbacks and challenges above, this study identified 21 DfMA constructs and 20 DfC constructs in the BCI. The constructs were further analysed to determine at which CVC stage the constructs actually transpire when applied during the ‘Circular Planning and Designing’ stage. These CVC stages were extracted from the works of Dewagoda, Ng, Kumaraswamy and Chen [20] and Dewagoda, Ng and

Kumaraswamy [37], and were refined to befit the context of a ‘circular modular building’, as shown in Figure 2.

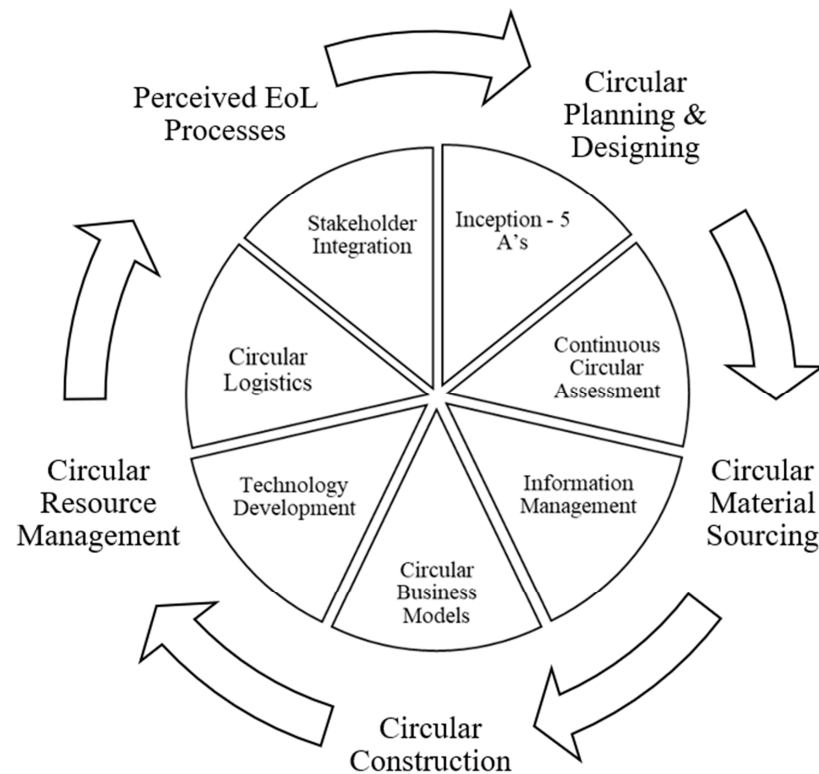


Figure 2. Circular construction value chain proposed for a circular modular building, adapted from [20,37].

While the sequential flow of the inner circle presents the ‘Primary Activities’ of value creation and retention, the outer circle encompasses the ‘Secondary Activities’ that support these primary activities throughout the WLC of a building, driving the CE transition in the BCI. According to Figure 2, the DfMA and DfC constructs were mapped across the WLC of a circular modular building, with each stage represented by a corresponding pictograph.

- Circular Material Sourcing  .
- Circular Manufacturing  .
- Circular Assembly  .
- Circular Resource Management  .
- Perceived EoL Processes  .

Table 3 presents the BCI-specific DfMA and DfC constructs identified in the extant literature.

It is noted that some constructs, such as ‘M8 Reduce the material demand of the building’ and ‘C15 Design out waste’, were discussed in both the DfMA and DfC literature, further reinforcing the synergies and commonalities of the two concepts. A descriptive analysis of the constructs based on the questionnaire survey is presented in the following sub-section.

Table 3. Constructs of DfMA and DfC in the BCI.

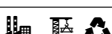
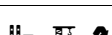
Value Chain Stage	Code	Construct	Sources
	M1	Reversible inter-module connections	[7,66–70]
	M2	Efficient module assembly on-site	[16,25,62,63,71,72]
	M3	Multi-functional building components	[36,63]
	M4	Standardised building components and modules	[29,61,62,68,73,74]
	M5	Scalable off-site module production	[25,31,72]
	M6	Integrated assemblies of building components	[63,70–72]
	M7	Repeat identical building components in the modules	[25,61,62]
	M8	Reduce the material demand of the building	[4,8,36,61,75]
	M9	Volumetric module design	[26,30,31,70,71,73,74,76–78]
	M10	Use affordable building materials	[36,62,70]
	M11	Use lightweight building materials and components	[25,73,79]
	M12	Use manufacturing-friendly building materials	[36,61,80]
	M13	Error-proof structural connections (Poka-Yoke)	[36,70–72]
	M14	Optimise spatial and structural layouts of modules	[62,70,73,78]
	M15	Compliance with quality and safety regulations during building construction	[25,36,74,78,81]
	M16	Streamlined handling and positioning of modules	[36,61–63,74]
	M17	Use self-locating and self-aligning inter-module connections	[36,82]
	M18	Logistically engineered module design	[31,36,74,78,79]
	M19	User-centred module design	[10,14,15,26,62,66,68,83]
	M20	Automation of building construction	[24,31,35,62,70,79,84]
	M21	Design to ensure safety during building construction and deconstruction	[23,25,72,80,81]
	C1	Design to close resource loops by treating physical resources as perpetual assets	[14,18,36,83–87]
	C2	Design to narrow resource loops by reducing materials and energy per module	[14,15,36,84,88]
	C3	Design to slow resource loops by extending the lifespan of building components	[36,75,84,85,89]
	C4	Flexible spatial layouts	[11,67,68,90]
	C5	Adaptable spatial layouts	[26,67,68,85,86,91]
	C6	Components that can be upgraded or modified	[9,15,18,29,69,77,92,93]
	C7	Reconfigurable spatial layouts and interchangeable components	[36,67,75]
	C8	Use durable building materials	[11,14,25,62,86]
	C9	Design for systematic disassembly of modules	[12,14,18,25,34,35,70,71,83,85,86,94–96]
	C10	Built-in serviceability of components and modules	[6,10,14,34,62,71,75,85,90]
	C11	Demountable and mobile module design	[7,18,26,67,70]
	C12	Restore and regenerate natural ecosystems	[10,14,35,68,83,84,86,96,97]
	C13	Integrate clean energy systems in the building design	[23,36,75,91]

Table 3. Cont.

Value Chain Stage	Code	Construct	Sources
	C14	Use secondary raw materials	[5,8,62,98,99]
	C15	Design out waste	[5,14,16,23,25,31,34,85,100]
	C16	Reduced energy consumption and carbon footprint of the building	[14,18,25,69,86,88,97]
	C17	Multiple-lifecycle use of modules	[26,36,75,101]
	C18	Recovery and reprocessing pathways of materials, components and assemblies	[6,15,66,98,99]
	C19	Design to foster deep personal feelings in the building	[24,75,79,102]
	C20	Lifecycle monitoring of building materials and components	[11,15,66,84,85,103]

3.2. Descriptive Analysis of DfMA Constructs and DfC Constructs in the BCI

Table 4 presents the descriptive statistics of DfMA constructs.

Based on the Mean and the Normalised Mean, ‘M2 Efficient module assembly on-site’, ‘M4 Standardised building components & modules’, ‘M21 Design to ensure safety during building construction & deconstruction’, ‘M9 Volumetric module design’ and ‘M8 Reduce the material demand of the building’ are the top 5 significant DfMA constructs in the BCI.

‘M2 Efficient module assembly on-site’ scored a Mean of 4.23 and ranked as the most significant DfMA construct. Given that ‘Design for Assembly (DfA)’ is an utmost priority of DfMA, efficient assembly on site is considered an important performance metric that focuses on reducing ‘construction’ or work on site [63,72]. Compared to traditional construction, IC itself saves 40% construction time [25]. Introducing DfMA can further enhance time efficiency by gaining better control of the assembly process, early layout planning of the construction site, and reducing defects in assembly [16]. These enhance ‘assemblability’ [79] when coupled with effective communication between contractor and manufacturer [62]. However, M2 also has a relatively high standard deviation, which implies a split in opinions. While a high percentage of respondents view efficient on-site assembly as ‘significant’, or ‘very significant’, a considerable proportion of respondents are in disagreement. This result may stem from differences among the respondents, arising, for example, from their industry experience, job role, or types of projects they were involved in, in perceiving whether efficient assembly is significant.

Table 4. Descriptive statistics of DfMA constructs in the BCI.

Code	DfMA Construct	S-W Test (Sig. <i>p</i>)	Standard Deviation	Mean	Normalised Mean	Rank
M1	Reversible inter-module connections	0.000	0.96	4.00	0.46	13
M2	Efficient module assembly on-site	0.000	0.94	4.23	1.00	1
M3	Multi-functional building components	0.000	0.93	3.91	0.24	17
M4	Standardised building components and modules	0.000	0.88	4.19	0.91	2
M5	Scalable off-site module production	0.000	1.03	4.07	0.61	7
M6	Integrated assemblies of building components	0.000	1.00	3.81	0.00	21
M7	Repeat identical building components in the modules	0.000	0.97	4.01	0.49	12
M8	Reduce the material demand of the building	0.000	0.97	4.17	0.86	5

Table 4. Cont.

Code	DfMA Construct	S-W Test (Sig. <i>p</i>)	Standard Deviation	Mean	Normalised Mean	Rank
M9	Volumetric module design	0.000	0.89	4.17	0.86	4
M10	Use affordable building materials	0.000	0.98	4.13	0.76	6
M11	Use lightweight building materials and components	0.000	0.95	4.05	0.57	10
M12	Use manufacturing-friendly building materials	0.000	0.95	3.98	0.41	14
M13	Error-proof structural connections (Poka-Yoke)	0.000	0.99	4.06	0.60	9
M14	Optimise spatial and structural layouts of modules	0.000	1.05	3.96	0.37	15
M15	Compliance with quality and safety regulations during building construction	0.000	0.95	4.07	0.61	8
M16	Streamlined handling and positioning of modules	0.000	1.00	3.87	0.16	18
M17	Use self-locating and self-aligning inter-module connections	0.000	0.93	3.92	0.27	16
M18	Logistically engineered module design	0.000	0.99	4.04	0.54	11
M19	User-centred module design	0.000	0.97	3.82	0.03	20
M20	Automation of building construction	0.000	0.95	3.87	0.16	18
M21	Design to ensure safety during building construction and deconstruction	0.000	1.01	4.19	0.90	3

‘**M4** Standardised building components & modules’ scored a Mean of 4.192 and ranked as the second most significant DfMA construct. Standardisation is a key DfMA principle [104,105]. Standardisation leads to less variation in the building design [62], which applies to non-structural service components [29], as well as module connections [68]. Standardisation enables mass production, enhancing economies of scale, as well as manufacturability, transportability and assemblability [73]. ‘**M21** Design to ensure safety during building construction & deconstruction’ scored a Mean of 4.186 and ranked as the third most significant DfMA construct. IC improves construction safety, reducing working at heights, risky and dangerous tasks, and the impacts of severe weather [25]. It also minimises noise, dust and disruption to neighbouring environments [23].

‘**M9** Volumetric module design’ scored a Mean of 4.17 and ranked as the fourth most significant DfMA construct as its standard deviation is lower than that of ‘**M8** Reduce the material demand of the building’. The Building and Construction Authority of Singapore [78] and Sonogo, Echeveste, and Galvan Debarba [77] define ‘modularity’ as the approach of organising complex products or processes into modules that are designed independently but function together through predefined interfaces to form an integrated product or process. Structural and functional independence, reduced interfaces and interactions with other modules and externalities are some features of modularisation [77]. The degree of modularisation is project-specific [30], and the highest level of modularisation is Modular Integrated Construction (MiC) [106] or Prefabricated Prefinished Volumetric Construction (PPVC) [78]. In the BCI, modularity is rather process-based rather than structural as it encapsulates several CVC stages, including manufacturing, assembly and operation [71]. Volumetric module design enables easy detachment, modification, replacement, and reuse of modules over time [73,77].

‘**M8** Reduce the material demand of the building’ scored a Mean of 4.17, which was equal to that of ‘**M9** Volumetric module design’, and ranked as the fifth most significant DfMA construct as its standard deviation is higher. Reducing the material input is a key principle of DfMA, which emanates from an economic point of view [107,108]. However, ‘dematerialisation’ is also identified as a core DfC principle. Reducing material demand, also

known as dematerialisation, typically refers to the reduction in raw material consumption associated with building construction. This, in turn, increases the material extraction and the material intensity of the BCI. For instance, ref. [8] highlights that material consumption is directly proportional to the economic growth of a country. Through the theoretical lens of value, CE adoption in the BCI aims to reduce overall resource demand [16]. Sharma, Kalbar, and Salman [4] predict a reduction in raw material consumption of up to 37% by 2050 in India by synergising CE principles in IC. Table 5 presents the descriptive statistics of DfC constructs.

Table 5. Descriptive statistics of DfC constructs in the BCI.

Code	DfC Construct	S-W Test (Sig. <i>p</i>)	Standard Deviation	Mean	Normalised Mean	Rank
C1	Design to close resource loops by treating physical resources as perpetual assets	0.000	0.83	4.19	0.95	2
C2	Design to narrow resource loops by reducing materials and energy per module	0.000	0.87	4.07	0.80	11
C3	Design to slow resource loops by extending the lifespan of building components	0.000	0.87	4.14	0.88	6
C4	Flexible spatial layouts	0.000	0.85	4.08	0.81	9
C5	Adaptable spatial layouts	0.000	0.95	4.06	0.78	12
C6	Components that can be upgraded or modified	0.000	0.91	3.98	0.68	17
C7	Reconfigurable spatial layouts and interchangeable components	0.000	0.91	3.99	0.69	15
C8	Use durable building materials	0.000	0.93	4.19	0.95	3
C9	Design for systematic disassembly of modules	0.000	0.86	4.10	0.83	7
C10	Built-in serviceability of components and modules	0.000	0.90	4.16	0.90	5
C11	Demountable and mobile module design	0.000	0.88	4.09	0.82	8
C12	Restore and regenerate natural ecosystems	0.000	0.95	3.99	0.69	14
C13	Integrate clean energy systems in the building design	0.000	0.95	4.02	0.73	13
C14	Use secondary raw materials	0.000	1.03	4.08	0.80	10
C15	Design out waste	0.000	0.90	4.23	1.00	1
C16	Reduced energy consumption and carbon footprint of the building	0.000	0.89	4.16	0.91	4
C17	Multiple-lifecycle use of modules	0.000	0.87	3.98	0.68	16
C18	Recovery and reprocessing pathways of materials, components and assemblies	0.000	0.94	3.77	0.41	19
C19	Design to foster deep personal feelings in the building	0.000	1.06	3.44	0.00	20
C20	Lifecycle monitoring of building materials and components	0.000	0.90	3.95	0.64	18

Based on the Mean and the Normalised Mean, ‘C15 Design out waste’, ‘C1 Design to close resource loops by treating physical resources as perpetual assets’, ‘C8 Use durable building materials’, ‘C16 Reduced energy consumption & carbon footprint of the building’ and ‘C10 Built-in serviceability of components & modules’ are the top 5 significant DfC constructs in the BCI. ‘C15 Design out waste’ scored a Mean of 4.23 and ranked as the most significant DfC construct. Designing out waste is a key CE principle that is also advocated by the BCI [109]. Stemming from CDW minimisation in CDWM, this construct underpins both the CE and IC [34,100]. ‘Reducing’ is central to solving the issue of CDW, which is realised through building design [5]. DfMA takes a step forward to prevent CDW through IC [23,31]. For example, CE places higher emphasis on concrete waste prevention over

valorisation in cement or concrete production [14]. Transferring on-site construction to OSC enhances governance of CW generation and reprocessing [25].

‘C1 Design to close resource loops by treating physical resources as perpetual assets’ scored a Mean of 4.19 and ranked as the second most significant DfC construct, as its standard deviation is lower than that of ‘C8 Use durable building materials’. Closing resource loops includes adopting CE strategies such as ‘recover’ and ‘recycle’. However, it is worth noting that recovery and recycling rank lowest in the waste hierarchy [110], indicating that they have the least priority in terms of resource treatment. Reinforced concrete, joint sealants, and glues render them challenging to recycle, given their chemical bonding, which complicates material separation [85]. Hence, concrete recycling is mainly limited to reprocessing as inputs to the production of cement and other composites [14]. However, metals, such as steel and aluminium, are theoretically considered 100% recyclable, as they can be melted down and recast without altering their fundamental chemical properties [14,18]. Given these limitations, IC and prefabrication are capable of acting as material banks that store and inventory materials for use in the next cycle [13,85].

‘C8 Use durable building materials’ scored a Mean of 4.19, which was equal to that of ‘C1 Design to close resource loops by treating physical resources as perpetual assets’ and ranked as the third most significant DfC construct, as its standard deviation was higher. Design for durability is a key circular design principle that urges the use of durable materials [14]. It also advocates for design that fosters change and resilience, promoting a building’s ability to withstand the test of time [11]. From an economic point of view, DfMA also urges longevity [62]. The authors further cite a case study, in which the governing aspect of selecting the external coating for the modular building’s envelope was the material with the longest service life, capable of withstanding harsh weather conditions over time. A caveat of using reinforced concrete, which is typically considered to have better structural performance, is that the steel reinforcement in concrete is vulnerable to corrosion, thereby limiting its longevity [14].

‘C16 Reduced energy consumption & carbon footprint of the building’ scored a Mean of 4.162 and ranked as the fourth most significant DfC construct. A strong emphasis has been placed on the BCI in terms of energy consumption and carbon emissions, given the longer service life of buildings and the growing volume of new building construction [97]. Kamali and Hewage [25] further emphasise the importance of environmental sustainability in IC, given the potential for mass production, which could have a detrimental environmental impact in terms of module transportation and assembly. However, IC is widely regarded as having better performance in terms of carbon emissions, energy consumption, and thermal insulation compared to its conventional counterpart [18,22]. For example, Pan and Zhang [69] showcased that both steel and concrete IC have significantly lower electricity consumption compared to traditional buildings. On the other hand, CE coupled with decarbonisation has proven to be remunerative, paving the way for future synergies [14].

‘C10 Built-in serviceability of components & modules’ scored a Mean of 4.156 and ranked fifth most significant DfC construct. Maintenance is crucial to extend the service life of a building [10]. ‘Maintenance’ essentially refers to the general upkeep of structures, preventing foreseeable impairments to the building [14]. DfMA application in building design is beneficial for maintenance [62], as different interfaces and layers of modules ensure accessibility and the possibility of replacing non-structural components, such as services, independently of structural components [6], for example, repainting the internal and external facades of a steel-container-based modular housing unit within its assumed lifecycle of 25 years [18]. However, the serviceability of modular buildings is governed

by business processes rather than technical specifications. Redefining business models for circular modular buildings should tend towards service-based ownership models such as ‘product as service’ [6,14,34,90].

3.3. Exploratory Factor Analysis (EFA) of DfCMA Constructs in the BCI

Having confirmed the suitability of EFA to analyse DfCMA constructs, factor analysis was carried out to unveil their latent structure. ‘Principal component analysis’ generated seven latent factor groups (CM1–CM7) with Eigenvalues greater than 1 [111], explaining 67.93% of the total variance. Analysing the conceptual domains accounting for the commonalities and shared themes, the latent factor groups were named as listed below.

- **CM1** Design for sustainable and resilient building life cycle management.
- **CM2** Design to facilitate lean building construction.
- **CM3** Human-centred building design.
- **CM4** Socio-technical design considerations of building systems.
- **CM5** Design to achieve economies of scale in building manufacturing.
- **CM6** Design for WLC resource sufficiency of the building.
- **CM7** Design for productivity and efficiency in building construction and deconstruction.

EFA was conducted using ‘principal component analysis’ as the extraction method and ‘Oblimin with Kaiser normalisation’ by way of oblique rotation as the rotation method. The rotation converged in 37 iterations. An oblique rotation method was used based on the theoretical assumption that the DfCMA constructs are correlated [112]. A pattern matrix that depicts the ‘unique contribution’ [112] of each construct to the latent factor groups was used for the interpretation. Table 6 presents the Pattern Matrix of DfCMA constructs, including the factor loadings, Eigenvalues and variance.

The cut-off value of 0.4 for factor loadings was used, as recommended in [113]. Three constructs, namely, ‘C12 Restore & regenerate natural ecosystems’, ‘C16 Reduced energy consumption & carbon footprint of the building’, and ‘C17 Multiple lifecycle use of modules’, could not successfully load into a latent factor group meeting the stipulated cut-off value. Hence, they had to be disregarded in the EFA as a standard practice to ensure construct validity [113].

The following sub-sections elaborate on each latent factor group in detail.

Table 6. EFA summary of DfCMA constructs in the BCI.

Code	Construct	Factor Loadings						
		CM1	CM2	CM3	CM4	CM5	CM6	CM7
CM1	Design for sustainable and resilient building life cycle management							
C5	Adaptable spatial layouts	0.750						
C4	Flexible spatial layouts	0.572						
C10	Built-in serviceability of components and modules	0.514						
C6	Components that can be upgraded or modified	0.513						
C8	Use durable building materials	0.484						
C7	Reconfigurable spatial layouts and interchangeable components	0.479						
CM2	Design to facilitate lean building construction							
M11	Use lightweight building materials and components		0.647					
M13	Error-proof structural connections (Poka-Yoke)		0.627					
M6	Integrated assemblies of building components		0.610					
M12	Use manufacturing-friendly building materials		0.492					

Table 6. Cont.

Code	Construct	Factor Loadings						
		CM1	CM2	CM3	CM4	CM5	CM6	CM7
M3	Multi-functional building components		0.482					
M14	Optimise spatial and structural layouts of modules		0.463					
M10	Use affordable building materials		0.450					
CM3	Human-centred building design							
M15	Compliance with quality and safety regulations during building construction			0.710				
M17	Use self-locating and self-aligning inter-module connections			0.608				
M16	Streamlined handling and positioning of modules			0.592				
M21	Design to ensure safety during building construction and deconstruction			0.563				
M19	User-centred module design			0.525				
M18	Logistically engineered module design			0.459				
M20	Automation of building construction			0.442				
C13	Integrate clean energy systems in the building design			0.400				
CM4	Socio-technical design consideration of building systems							
C19	Design to foster deep personal feelings in the building				0.895			
C20	Lifecycle monitoring of building materials and components				0.664			
C18	Recovery and reprocessing pathways of materials, components and assemblies				0.498			
C11	Demountable and mobile module design				0.468			
CM5	Design to achieve economies of scale in building manufacturing							
M7	Repeat identical building components in the modules					0.512		
M5	Scalable off-site module production					0.507		
M4	Standardised building components and modules					0.483		
CM6	Design for WLC resource sufficiency of the building							
C1	Design to close resource loops by treating physical resources as perpetual assets						0.760	
C15	Design out waste						0.637	
C2	Design to narrow resource loops by reducing materials and energy per module						0.590	
C3	Design to slow resource loops by extending the lifespan of building components						0.577	
C14	Use secondary raw materials						0.463	
CM7	Design for productivity and efficiency in building construction and deconstruction							
M2	Efficient module assembly on-site							0.765
M9	Volumetric module design							0.594
M1	Reversible inter-module connections							0.554
M8	Reduce the material demand of the building							0.479
C9	Design for systematic disassembly of modules							0.434
Eigenvalue		19.500	2.218	1.689	1.220	1.154	1.052	1.017
Variance (%)		47.560	5.411	4.119	2.975	2.816	2.566	2.480
Cumulative Variance (%)		47.560	52.971	57.090	60.064	62.880	65.446	67.926

3.3.1. CM1: Design for Sustainable and Resilient Building Life Cycle Management

‘CM1 Design for sustainable and resilient building life cycle management’ has an Eigenvalue of 19.5 that explains 47.56% of the total variance. CM1 includes six DfC constructs, all focusing on the operational phase of a building, which is critical in realising a circular modular building [61]. For example, Satola, Kristiansen, Houlihan-Wiberg, Gustavsen, Ma and Wang [18] showcased that the operational phase of a container modular

housing unit has the highest environmental impact, including energy consumption. Buildings that facilitate flexibility and adaptability are crucial for ensuring the sustainability and resilience of a building while also addressing changing user needs [11,90]. However, the existing building stock is mainly monolithic and non-standardised, limiting its ability to transform according to user needs [95]. Hence, CE advocates for designing buildings with the ability to transform in either mono-functional or trans-functional contexts [67]. Therefore, ‘C5 Adaptable spatial layouts’ and ‘C4 Flexible spatial layouts’ promote overall longevity by either changing according to changing user needs or evolving in response to new conditions, respectively. Kyrö, Jylhä and Peltokorpi [26] point out that relocatable modular buildings are capable of high flexibility and adaptability. Modularity also facilitates easy upgrades and modifications, as seen in ‘C6 Components that can be upgraded or modified’ [9], given the importance of evaluating the environmental impact of such practices [77]. An existing common practice in C6 is building retrofitting, which has proven benefits in terms of reducing carbon emissions compared to new constructions [91]. ‘C7 Reconfigurable spatial layouts & interchangeable components’ supports the concept of ‘reversible configuration’ as put forward by the ‘BAMB’ project [13]. It implies the ability of a building to reconfigure and interchange its elements without damaging the overall structure [67]. The other two constructs of CM1, namely, ‘C8 Use durable building materials’ and ‘C10 Built-in serviceability of components & modules’, are discussed in detail in Section 3.2.

3.3.2. CM2: Design to Facilitate Lean Building Construction

‘CM2 Design to facilitate lean building construction’ has an Eigenvalue of 2.218 that explains 5.41% of the total variance. CM2 includes seven DfMA constructs that align with LC principles. The goals of DfMA and LC are different. While LC aims to increase value by minimising CW, DfMA aims to increase module manufacturing efficiency and assembly productivity through design optimisation [31]. However, DfMA can be employed to reduce assembly and material costs [63], which aligns with the primary goal of LC. On the other hand, LC encourages CDWM and DfC through CW reduction [85]. Based on these premises, LC can be proposed as a bridge to synergise DfMA and DfC in the BCI. For example, Benachio, Freitas Maria do Carmo, and Tavares Sergio [33] recognise IC as an enabler of CE through the implementation of LC principles, such as reducing non-value-adding activities, increasing process transparency, and balancing flow improvement with conversion improvement. ‘M3 Multi-functional building components’ advocates for designing building elements to be multi-functional as well as multi-use [63]. The generic DfMA principle, ‘minimise part count’ [105,114], is translated to the BCI as ‘M6 Integrated assemblies of building components’. The intention is to reduce on-site assembly through pre-assemblies.

Affordability is a key criterion in promoting IC as a promising approach to address housing needs in rapidly developing regions, particularly in Asia [18]. While IC is expected to generate some cost savings, ‘M10 Use affordable building materials’ further promotes affordability through using low-cost building materials. ‘M11 Use light-weight building materials and components’ is critical to reduce the overall weight of the building to improve the efficiency and productivity in manufacturing and assembly [79]. For example, Bao, Laovisutthichai, Tan, Wang, and Lu [73] cite a case study that utilises lightweight concrete in an IC project, resulting in a 33% reduction in the overall weight of the building. However, caution must be taken in material-lightened designs so as not to jeopardise the functionality and structural performance of the building [25,73,79]. Strength-enhanced fibre-reinforced cementitious composites [69] are an example of ‘M12 Use manufacturing-friendly building materials’ in the BCI. ‘M13 Error-proof structural connections (Poka-Yoke)’

builds on the Japanese lean tool ‘mistake-proofing assembly operations’ [72] facilitated through design optimisation. The generic DfMA principle ‘simplified design’ [105,114] is adapted in the context of the BCI as ‘**M14** Optimise spatial and structural layouts of modules’. Design simplification in IC involves minimising the quantity and complexity of building elements in terms of geometry and arrangements, resulting in a “simple and flat design” [73] (pg. 330).

3.3.3. CM3: Human-Centred Building Design

‘CM3 Human-centred building design’ has an Eigenvalue of 1.689 that explains 4.119% of the total variance. CM3 includes seven DfMA constructs and one DfC construct that enhance the health and well-being of the stakeholders across the WLC of a building. CM3 supports social sustainability by providing a safer working environment, reducing the accident rate, and maintaining a cleaner working environment, which, in turn, reduces dust and noise during the manufacturing and assembly CVC stages [22,69,85]. However, CM3 is not limited to the building construction phases, but also includes stakeholders involved in the WLC of the circular modular building, such as building occupants. ‘**M15** Compliance with quality and safety regulations during building construction’ is a general requirement even in traditional building construction. However, additional caution must be exercised, given the novelty of the method of construction of modular buildings, for example, during the transportation of modules [25], and the complexity of module connections [69]. This includes ‘**M16** Streamlined handling and positioning of modules’ during module manufacturing, transportation and assembly on site [61]. Construction technologies are advancing to include ‘**M17** Use self-locating & self-aligning inter-module connections’ that also self-lock, self-centre or self-recover upon module placement [82].

As highlighted previously under **CM3**, logistics play a pivotal role in IC. Hence, logistic-optimised design features such as size and weight optimisation of modules [62] and corner protection [72] are directed under ‘**M18** Logistically engineered module design’. ‘**M19** User-centred module design’ focuses on aspects such as material toxicity [66,68], indoor air quality and thermal comfort [26], and avoiding environmental pollution [10] during building design. ‘**M20** Automation of building construction’ replaces manual work-intensive processes using digital and other advanced technologies [62]. Such a technology-rationalised modular building not only improves productivity but also increases product quality through precision and provides a safer work environment during manufacturing and assembly [31]. Additive manufacturing is one of the most recent innovations in automation, enabling the production of unique geometric structures [14]. ‘**M21** Design to ensure safety during building construction & deconstruction’ is discussed in detail in Section 3.2. Adoption of renewable energy retrofitting measures, such as Building Integrated Photovoltaic (BIPV) panels, solar thermal collectors for water heating, and building-integrated wind turbines [91], exemplifies the principle of ‘**C13** Integrate clean energy systems in the building design’.

3.3.4. CM4: Socio-Technical Design Consideration of Building Systems

‘CM4 Socio-technical design consideration of building systems’ has an Eigenvalue of 1.22 that explains 2.975% of the total variance. CM4 includes four DfC constructs that overlook the socio-technical considerations of a building. The fundamental that “value defined by absolute parameters, is not absolute” [68] (pg. 306). Hence, cohesive consideration of both social values and technical considerations is advocated. In order to achieve ‘**C19** Design to foster deep personal feelings in the building’, the design process of the circular modular building can be improved to enhance user satisfaction by engaging them in the design process [24]. ‘Mass customisation’ is another concept that can support C19.

While IC is based on mass production, mass customisation gives the end-users the flexibility to customise their modular building [24]. Hence, by engaging them in the design process, the benefits of standardisation can be yielded by facilitating customisation [26]. ‘C11 Demountable and mobile module design’ is one technical consideration that overlooks not only the demountability but also the rapid relocatability of modules [26]. For example, steel container housing modules have high reusability potential as they can be easily dismounted and rapidly relocated to a different location [18]. C11 should be supplemented with ‘C18 Recovery & reprocessing pathways of materials, components & assemblies’ for the successful synergy of CE principles in IC. Dewagoda, Ng, Kumaraswamy and Chen [38] recognised the lack of established infrastructure to recover and reprocess materials, products, and components at their perceived EoL as one of the major limitations to adopting DfC in the BCI. The requirement not only stresses the technicality but also the requirement of modified business processes to enable ‘reverse logistics’ [38,98]. Considering these concerns, Dewagoda, Kumaraswamy, Chen, Ng and Jayathunga [36] propose the following DfCMA planning strategies that should be implemented in a top-to-bottom approach:

- Developing take-back channels with module, material or product manufacturers and suppliers.
- Setting up resource recovery subsidies to treat waste generated during different phases of the building CVC.
- Standardising and regulating the quality and consistent supply of recovered building elements.
- Promoting circular markets to advertise, locate and sell recovered building elements.
- Developing regional material banks, including assessment, conditioning, storage and certification of recovered building elements.
- Promoting ‘Industrial Symbiosis’ as a means of sharing resources among different industries.

‘C20 Lifecycle monitoring of building materials & components’ urges that the building materials and components are traced across the WLC of a circular modular building [11]. One of the prominent advancements of C20 is the concept of ‘material passports’ by BAMB [13]. Technical considerations are not only limited to the above but also to other revolutionary technologies applicable in DfCMA, such as Geographic Information System (GIS) for urban mining [87] and Building Information Modelling (BIM) in building environmental assessment [115], Augmented Reality (AR), and Internet of Things (IoT) [116].

3.3.5. CM5: Design to Achieve Economies of Scale in Building Manufacturing

‘CM5 Design to achieve economies of scale in building manufacturing’ has an Eigenvalue of 1.154 that explains 2.816% of the total variance. CM5 includes three DfMA constructs that support achieving economies of scale in building manufacturing. The maximum benefits of DfMA are yielded when the production reaches economies of scale. Hence, the economic benefits of DfMA are not immediate and are realised over time with economies of scale [31]. Given the same reason, it might be cheaper to use a traditional method of construction rather than IC of irregular structures or non-repetitive modules [25]. ‘M4 Standardised building components & modules’ is discussed in detail in Section 3.2. Scalability is a crucial factor in DfMA, as mass production is the heart of DfMA. Owing to the same rationale, emphasis is placed on accounting for the environmental impacts of IC, as its effects significantly increase with manufacturing, transportation, and assembly, particularly with scalability under the ‘M5 Scalable off-site module production’ approach. ‘M7 Repeat identical building components in the modules’ is inextricably linked to M4, as mass production can only be realised through the repetition of standardised building components in the design across projects.

3.3.6. CM6: Design for WLC Resource Sufficiency of the Building

‘CM6 Design for WLC resource sufficiency of the building’ has an Eigenvalue of 1.052 that explains 2.566% of the total variance. CM6 includes five DfC constructs that advocate for the resource sufficiency mindset. CE demands not only addressing excessive production patterns but also transforming unnecessary consumption patterns [8]. Accordingly, sufficiency-based approaches of CE in the BCI advocate for elimination of ‘redundant’ or ‘unnecessary’ parts, which is yet to be addressed [14]. Resource sufficiency extends beyond resource efficiency. Resource efficiency encompasses reducing environmental impact through strategies such as reducing waste generation, replacing non-renewable materials with recycled and renewable materials, extending the durability, and reducing the material mass of the building [35]. The DfC constructs ‘C1 Design to close resource loops by treating physical resources as perpetual assets and ‘C15 Design out waste’ that purports resource sufficiency in DfCMA are discussed in detail in Section 3.2. ‘C2 Design to narrow resource loops by reducing materials & energy per module’ not only calls for ‘reducing’ but also ‘rethinking’ building design. This is achieved through modified business models of IC, which promote responsible resource management across the WLC of the building [34].

‘C3 Design to slow resource loops by extending the lifespan of building components’ is expected to focus largely on the technical cycle of materials during the use phase over the EoL of a circular modular building. Marsh, Velenturf and Bernal [14] define ‘repairing’ as repairing damage caused to a building component, ‘refurbishment’ as replacing a damaged element with a new product to extend the service life, and ‘remanufacturing’ as using elements of a building that have already reached their perceived EoL in a new building. While reuse and refurbishment give a second life to existing buildings or building components, remanufacturing returns the components to the manufacturer or supplier in as-new condition to serve a different building [10]. However, reuse is always prioritised over remanufacturing in accordance with the ‘waste hierarchy’ [14]. Bianchi and Cordella [8] assert that regions with high CE adoption have a low rate of natural resource extraction, as the circular material use rate is higher in such regions. Here, secondary raw materials govern the circular material use rate as in ‘C14 Use secondary raw materials’. C14 is highly influenced by the purchase intention of BCI stakeholders, which is shaped by their perceived value [5], and is governed by the quality, availability, and cost of secondary raw materials [98].

3.3.7. CM7: Design for Productivity and Efficiency in Building Construction and Deconstruction

‘CM7 Design for productivity and efficiency in building construction and deconstruction’ has an Eigenvalue of 1.017 that explains 2.48% of the total variance. CM7 includes four DfMA constructs and one DfC construct that aim to increase the efficiency of building manufacturing. DfMA improves the productivity of IC, as many operations can be carried out simultaneously without disruption [25,69]. DfMA is also proven to be time-, cost- and design-efficient as it optimises the design to address any inefficiencies in the downstream processes [29]. However, the efficiency of IC is yet to be realised in the BCI given its inherent incumbrances that demand extensive planning and designing [36,61]. Flexible joints found in the generic DfMA literature are adapted in the BCI context as ‘M1 Reversible inter-module connections’. Most of the BCI literature promotes dry module connections, such as mechanical or magnetic joints, rather than concrete-filled, mortar-sealed, welded, or glued joints [7,66,68]. Dry connections facilitate functional independence [67], which not only simplifies module assembly but also supports module disassembly [7,69]. ‘C9 Design for systematic disassembly of modules’ circular design principles,

such as design for deconstruction and design for disassembly [25,34,94,95]. For example, welded steel–concrete composite floor systems require replacement with demountable shear connectors to facilitate future disassembly [16]. Satola, Kristiansen, Houlihan-Wiberg, Gustavsen, Ma and Wang [18] pinpoint that the environmental impacts of steel module disassembly are the same as those of assembly. However, module disassembly is limited by the factors given below:

- Existing buildings and components are not designed for disassembly.
- Tools for the deconstruction of existing buildings often do not exist.
- The disposal cost of demolition waste is lower than that of deconstruction and reprocessing.
- Module disassembly is more time-consuming and complicated than demolition.
- Mechanisms to assure the quality of recovered material are unavailable.
- Existing regulatory frameworks do not mandate the reuse of building materials and components.
- The economic and environmental benefits of building deconstruction are not well verified and documented [7].

Other DfMA constructs under CM7, namely, ‘**M2** Efficient module assembly on-site’, ‘**M9** Volumetric module design’, and ‘**M8** Reduce the material demand of the building’, are discussed in detail in Section 3.2.

Figure 3 summarises the findings of EFA in terms of the 07 latent factors (CM1–CM7), their themes and related key constructs.

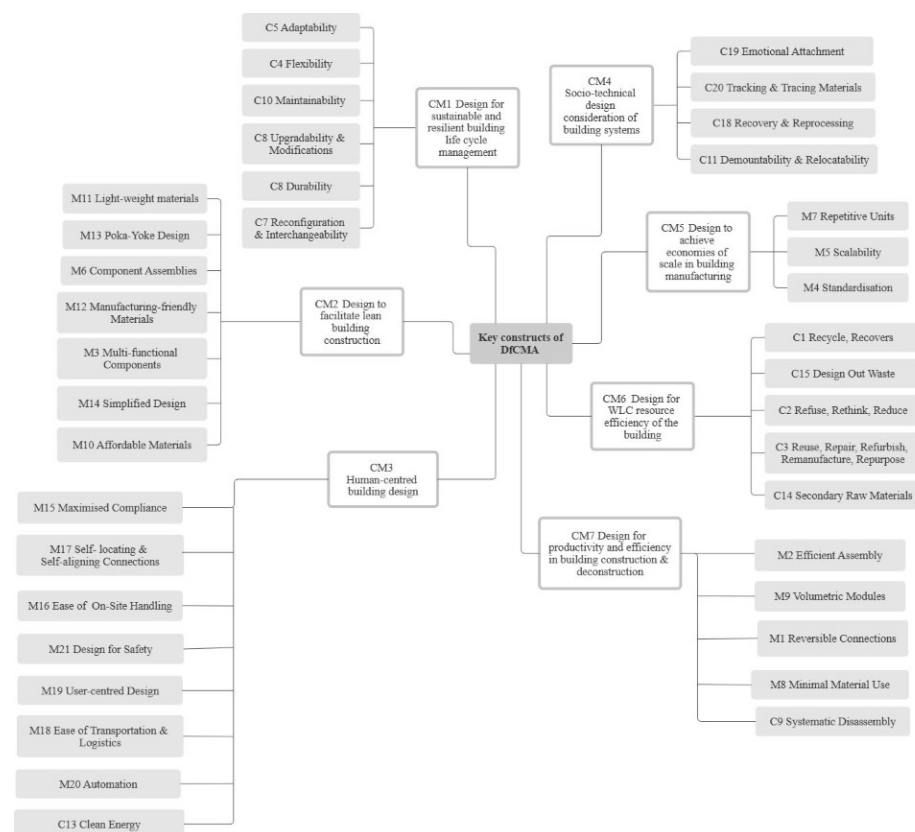


Figure 3. Latent factors and themes of key constructs of DfCMA.

3.4. Fuzzy Synthetic Evaluation (FSE) of DfCMA Constructs in the BCI

FSE was carried out following the EFA presented in the previous sub-section. Table 7 summarises the weightings and the MFs of the DfCMA constructs and the latent factor groups.

Table 7. FSE summary of DfCMA constructs in the BCI.

Code	Constructs	Mean (μ_i)	Weighting (W_i)	MF (Level 3)	MF (Level 2)	MF (Level 1)
Key constructs of DfCMA						0.02, 0.05, 0.18, 0.38, 0.37
CM1	Design for sustainable and resilient building life cycle management	24.46	0.16		0.01, 0.05, 0.16, 0.41, 0.37	
C5	Adaptable spatial layouts	4.06	0.17	0.01, 0.07, 0.15, 0.40, 0.38		
C4	Flexible spatial layouts	4.08	0.17	0.01, 0.02, 0.19, 0.43, 0.35		
C10	Built-in serviceability of components and modules	4.16	0.17	0.01, 0.04, 0.16, 0.38, 0.42		
C6	Components that can be upgraded or modified	3.98	0.16	0.01, 0.08, 0.16, 0.46, 0.31		
C8	Use durable building materials	4.19	0.17	0.01, 0.05, 0.14, 0.34, 0.46		
C7	Reconfigurable spatial layouts and interchangeable components	3.99	0.16	0.01, 0.06, 0.17, 0.45, 0.31		
CM2	Design to facilitate lean building construction	27.90	0.18		0.02, 0.06, 0.19, 0.38, 0.35	
M11	Use lightweight building materials and components	4.05	0.15	0.01, 0.07, 0.16, 0.40, 0.37		
M13	Error-proof structural connections (Poka-Yoke)	4.06	0.15	0.03, 0.04, 0.17, 0.37, 0.40		
M6	Integrated assemblies of building components	3.81	0.14	0.01, 0.10, 0.23, 0.37, 0.28		
M12	Use manufacturing-friendly building materials	3.98	0.14	0.02, 0.05, 0.19, 0.41, 0.33		
M3	Multi-functional building components	3.91	0.14	0.02, 0.04, 0.25, 0.40, 0.29		
M14	Optimise spatial and structural layouts of modules	3.96	0.14	0.04, 0.06, 0.17, 0.38, 0.36		
M10	Use affordable building materials	4.13	0.15	0.01, 0.07, 0.15, 0.33, 0.44		
CM3	Human-centred building design	31.80	0.21		0.02, 0.06, 0.19, 0.39, 0.34	
M15	Compliance with quality and safety regulations during building construction	4.07	0.13	0.01, 0.06, 0.16, 0.38, 0.38		
M17	Use self-locating and self-aligning inter-module connections	3.92	0.12	0.02, 0.05, 0.20, 0.44, 0.29		
M16	Streamlined handling and positioning of modules	3.87	0.12	0.03, 0.06, 0.20, 0.42, 0.29		
M21	Design to ensure safety during building construction and deconstruction	4.19	0.13	0.02, 0.06, 0.11, 0.32, 0.49		
M19	User-centred module design	3.82	0.12	0.01, 0.08, 0.26, 0.37, 0.28		
M18	Logistically engineered module design	4.04	0.13	0.02, 0.07, 0.17, 0.36, 0.39		
M20	Automation of building construction	3.87	0.12	0.01, 0.07, 0.25, 0.39, 0.29		
C13	Integrate clean energy systems in the building design	4.02	0.13	0.02, 0.05, 0.17, 0.41, 0.35		
CM4	Socio-technical design consideration of building systems	15.24	0.10		0.02, 0.06, 0.25, 0.40, 0.27	
C19	Design to foster deep personal feelings in the building	3.44	0.23	0.05, 0.13, 0.33, 0.34, 0.16		
C20	Lifecycle monitoring of building materials and components	3.95	0.26	0.02, 0.02, 0.25, 0.41, 0.30		

Table 7. Cont.

Code	Constructs	Mean (μ_i)	Weighting (W_i)	MF (Level 3)	MF (Level 2)	MF (Level 1)
C18	Recovery and reprocessing pathways of materials, components and assemblies	3.77	0.25	0.02, 0.07, 0.26, 0.43, 0.22		
C11	Demountable and mobile module design	4.09	0.27	0.01, 0.04, 0.18, 0.40, 0.37		
CM5	Design to achieve economies of scale in building manufacturing	12.27	0.08		0.02, 0.05, 0.15, 0.38, 0.40	
M7	Repeat identical building components in the modules	4.01	0.33	0.03, 0.04, 0.17, 0.41, 0.35		
M5	Scalable off-site module production	4.07	0.33	0.02, 0.07, 0.14, 0.35, 0.42		
M4	Standardised building components and modules	4.19	0.34	0.01, 0.04, 0.14, 0.37, 0.44		
CM6	Design for WLC resource efficiency of the building	20.71	0.14		0.01, 0.04, 0.16, 0.37, 0.42	
C1	Design to close resource loops by treating physical resources as perpetual assets	4.19	0.20	0.01,0.02,0.16,0.40,0.41		
C15	Design out waste	4.23	0.20	0.01, 0.04, 0.16, 0.31, 0.49		
C2	Design to narrow resource loops by reducing materials and energy per module	4.07	0.20	0.01, 0.03, 0.22, 0.38, 0.37		
C3	Design to slow resource loops by extending the lifespan of building components	4.14	0.20	0.01, 0.04, 0.16, 0.40, 0.40		
C14	Use secondary raw materials	4.08	0.20	0.02,0.08,0.13,0.34,0.43		
CM7	Design for productivity and efficiency in building construction and deconstruction	20.66	0.14		0.01, 0.04, 0.16, 0.37, 0.42	
M2	Efficient module assembly on-site	4.23	0.20	0.02, 0.03, 0.12, 0.35, 0.48		
M9	Volumetric module design	4.17	0.20	0.01, 0.04, 0.18, 0.34, 0.44		
M1	Reversible inter-module connections	4.00	0.19	0.02, 0.05, 0.21, 0.37, 0.36		
M8	Reduce the material demand of the building	4.17	0.20	0.01, 0.07, 0.11, 0.35, 0.46		
C9	Design for systematic disassembly of modules	4.10	0.20	0.01, 0.03, 0.16, 0.44, 0.36		

Based on the weightings and MFs of the DfCMA constructs, the significance indices of the latent factor group, i.e., second-level MFs, were calculated using Equation (9) and are presented in Table 8.

Table 8. Significance indices of latent factor groups of DfCMA constructs in the BCI.

Code	Construct	Significant Indices of Level 2 MFs
CM1	Design for sustainable and resilient building life cycle management	4.077
CM2	Design to facilitate lean building construction	3.988
CM3	Human-centred building design	3.978
CM4	Socio-technical design considerations of building systems	3.825
CM5	Design to achieve economies of scale in building manufacturing	4.091
CM6	Design for WLC resource sufficiency of the building	4.143
CM7	Design for productivity and efficiency in building construction and deconstruction	4.134

It is observed that the most crucial latent factor group with the highest significance index is ‘**CM6** Design for WLC resource sufficiency of the building’, followed by ‘**CM7** Design for productivity and efficiency in building construction and deconstruction’ and ‘**CM5** Design to achieve economies of scale in building manufacturing’. Based on the weightings and MFs of DfCMA constructs and latent factor groups, the overall significance index, i.e., the first-level MF, was calculated using Equation (10). The overall significance index of DfCMA constructs, thus calculated, was 4.033. This value signifies that, collectively, DfCMA constructs have a significant impact on realising a circular modular building by synergising DfMA and DfC in IC.

4. Discussion

The Dutch government, a pioneer in CDWM and CE, piloted ‘Industrialised, Flexible and Demountable (IFD) buildings’ during the post-World War II period as a viable modern construction methodology to address the needs of rapid urbanisation economically [117]. IFD buildings are characterised by building-scale thinking (system-, product-, material-scale), a multidisciplinary design approach, flexible interiors, modular dimensioning and dismantlability based on a multi-dimensional perspective of value [118]. While IFD buildings are commended for time and cost efficiency, they are largely underpinned by what we take as linear (rather than circular) economic principles, which prevailed at the time IFD was conceived to address the needs then, as above. Since IFD buildings primarily aim to achieve higher productivity, they promote mass production, which contradicts the core principle of CE, namely, responsible production and consumption based on sufficiency, as outlined in DfCMA. DfCMA, a concept still under development by the authors, is committed to addressing the tension between mass production, as nuanced in DfMA, and sufficiency, as advocated in DfC. The goal is to leverage the benefits of mass production (such as economies of scale) with a resource-conscious mindset. For example, while IFD buildings prioritise ‘cost per unit’, DfCMA places higher emphasis on the quality and durability of materials, i.e., ‘value per unit’. Hence, while IFD buildings are characterised by affordability at the BoL, circular modular buildings aim at the maximum possible value across their WLC.

Hence, circular modular buildings can be viewed as a holistic advancement of IFD buildings. However, IFD buildings have a great circular potential. For example, the dry construction method [117] used in IFD supports ‘M1 Reversible inter-module connections’,

which, in turn, facilitates ‘C9 Design for systematic disassembly of modules’ and ‘C11 Demountable and mobile module design’, which is the basic idea of demountability in IFD. The demountability of IFD buildings coupled with relocatability advances ‘C17 Multiple lifecycle use of modules’. The mass-customisability of IFD buildings also supports circularity. The internal non-load-bearing structure of IFD buildings is designed to accommodate user preferences and changing user needs [118], which is comparable to ‘C4 Flexible spatial layouts’ and ‘C5 Adaptable spatial layouts’ in DfCMA. Hence, an IFD building is viewed as a ‘sustainable building’ [118] that contributes to sustainable construction [7]. Although the inherent waste reduction and resource-efficient features of IC align with sustainable construction, their inability to retain value across the WLC of a building requires significant improvement.

The European-Union-funded project, BAMB, advocates for the ‘reversible buildings’ concept that is expected to reverse the space (adaptability), reverse the structure (reconfiguration and upgrade), and reverse the material (deconstruction) [67]. Being a CE-inspired building concept, reversible buildings inspired the concept of reversibility of circular modular buildings. For example, DfCMA constructs such as ‘C4 Flexible spatial layouts’, ‘C5 Adaptable spatial layouts’, ‘C6 Components that can be upgraded or modified’, ‘C7 Reconfigurable spatial layouts & interchangeable components’, ‘C9 Design for systematic disassembly of modules’, and ‘M1 Reversible inter-module connections’ are compatible with a reversible building. Durmisevic [67] provides an extensive technical protocol for designing reversible buildings, which can be applied in the design of a circular modular building. A reversible building concept, supported by material passports, promotes the idea of a circular building. Even though slowing resource loops is promoted by reversible buildings, the extent to which they consider narrowing resource loops is debatable. Accordingly, DfCMA heralds a distinctly dual-benefited IC that transcends resource efficiency in a value-added DfMA system, which also facilitates CE transition in the BCI. The reversible building concept primarily focuses on the design of the physical building to support modularity, flexible and adaptable layouts, and reusable components. In contrast, DfCMA is also supplemented with supporting business and management processes to enable the overall functioning of a circular modular building based on its circular CVC. As depicted in Figure 2 (under Section 3.1), the supporting activities of DfCMA are as follows:

- Stakeholder Integration.
- Inception (5 As: (Awareness, Attitude, Acceptance, Agreement and Apprehension))
- Continuous Circular Assessment.
- Information Management.
- Circular Business Models
- Technology Development.
- Circular Logistics [20,37].

Hence, DfCMA is an overarching framework that combines both hard (technical) and soft (managerial) aspects of CE transition in the BCI through IC. Although a solid practical example or case encapsulating the DfCMA is currently unavailable, the ‘transitional housing’ concept demonstrates high potential for implementing DfCMA. For example, transitional housing in Hong Kong is being developed as a means of providing temporary housing for households until they can be accommodated in long-term housing, which already has circular features embedded [119]. IC is increasingly gaining recognition and interest in Hong Kong as a means of delivering buildings with high productivity [22,106]. Hence, the Government of Hong Kong’s transitional housing scheme has high potential for integrating CE and IC to promote DfCMA in a top-down approach. In addition, in a previous publication, the authors have investigated the practical application of DfCMA

in an ongoing IC project and proposed a checklist for practitioners to synergise DfC and DfMA in modular buildings [36].

5. Limitations

It is understood that DfCMA constructs do not stand alone and have stronger interrelationships among themselves, thus demanding trade-offs based on multi-criteria decision-making [20]. For example, a design conflict may arise between durability and modularity, as a durable design promotes the extension of building life, while modularity suggests a relatively shorter building life cycle [76]. On the other hand, specifying the use of secondary raw materials in new building constructions risks promoting CDW valorisation over CDW prevention [85]. Additionally, a healthy debate may be sparked by the choice between using a secondary raw material that has been reprocessed and a virgin material with a lower embodied carbon percentage [14]. Hence, this study is limited to identifying the nominal constructs of DfCMA through a quantitative approach. While strong correlations between the key constructs are noted through this approach, their inter-dependencies and influences in terms of causality are not taken into account. In order to evaluate the extent and direction of the causal relationships among the key constructs of DfCMA, further research employing methods such as 'Structural Equation Modelling' is recommended. Since this study aimed only to identify the key constructs of DfCMA, it does not delve into the complex interactions that exist among them. It is also crucial to investigate how the DfCMA constructs are enacted within different building layers, namely, 'Building level', 'Systems, assemblies and sub-assemblies' level, 'Product and component level', and 'Material level'. Hence, future research may model the complex relationships between the DfCMA constructs using methods such as 'Systems Dynamics Modelling'.

The results are subject to the inherent methodological limitations of the questionnaire survey method, including any possible researcher bias and sampling bias. For instance, the sample in this study is not professionally or geographically balanced. Since a new concept in DfCMA was proposed, the technical feasibility and financial and economic viability were considered important. Assuming this primarily concerns engineers in terms of technicality and quantity surveyors in terms of economics and finance, their stronger representation in the sample may be useful in that context. Secondly, at this initial stage, this study primarily aims at theoretical generalisation; so, more construction manager inputs may be warranted at the next stage. Also, the results do not indicate a statistically significant difference among the different regions nor among the job roles. This study presents part of the findings from ongoing research on DfCMA implementation in the Asian continent, conducted by the authors, who have an established relevant network in the same region. This has contributed to the geographical composition of the sample, aiming at knowledgeable and reliable responses. Furthermore, this study primarily aims at theoretical generalisation, and the results do not indicate a statistically significant difference among the different regions. However, further research is recommended to include a balanced sample to minimise any potential bias.

The results are also subjected to the inherent methodological limitations of the data analysis methods, i.e., EFA and FSE. For example, C12, C16, and C17 were excluded from the EFA because their factor loadings were below the cut-off value of 0.4. However, pertinent to the theoretical importance of these constructs, they may need to be included in future research analyses. The conceptual/theoretical nature of this study did not capture the complexity and depth of decision-making required to scrutinise the optimal synergy level of DfC and DfMA to deliver a circular modular building across its WLC. For example, although the significance of DfCMA constructs was captured quantitatively, further research is needed to gain an in-depth understanding of the feasibility and practicality of

these constructs, as well as their environmental, economic, and social impacts upon implementation. The decision-making related to the synergy level of DfC and DfMA is highly project- and region-specific, influenced by both endogenous factors (such as stakeholder priorities and constraints) and exogenous factors (such as market conditions, policy and regulatory frameworks, and financial structure). Hence, follow-up context-specific, in-depth research methodologies, including case studies, are needed to ensure the transferability of these findings.

6. Conclusions

This study quantitatively evaluates the key constructs of Design for Circular Manufacturing and Assembly (DfCMA). DfCMA is an overarching design framework proposed by the authors in their previous publications that envisages synergising circularity (Design for Circularity (DfC)) and modularity (Design for Manufacturing and Assembly (DfMA)) in the Building Construction Industry (BCI). Following a thorough literature review, 21 DfMA constructs and 20 DfC constructs were identified. Data was collected using a closed-ended questionnaire survey that was distributed globally, following a pilot survey. A total of 167 valid responses were received, and the data was analysed descriptively, followed by Exploratory Factor Analysis (EFA) and Fuzzy Synthetic Evaluation (FSE). Having identified DfMA and DfC constructs in the BCI through the literature review, seven consolidated DfCMA constructs, ‘Design for sustainable and resilient building life cycle management’, ‘Design to facilitate lean building construction’, ‘Human-centred building design’, ‘Socio-technical design considerations of building systems to achieve economies of scale in building manufacturing’, ‘Design for Whole Life Cycle (WLC) resource sufficiency of the building’, and ‘Design for productivity and efficiency in building construction and deconstruction’, were propounded. This study also emphasises the significance of those DfCMA constructs in advancing the DfCMA framework in the BCI. This study contributes to the theory by quantitatively analysing and putting forward the key constructs of DfCMA. This timely study further encourages BCI practitioners to appreciate and consider using the mechanisms outlined in DfCMA for adopting Circular Economy (CE) principles in Industrialised Construction (IC). This study further prompts policymakers to take a rationalised and systematic approach in strategy formulation and decision-making in the adoption of a CE and IC in the BCI.

Author Contributions: Conceptualisation, K.G.D., S.T.N., M.M.K. and J.C.; Formal Analysis, K.G.D., S.T.N., M.M.K. and J.C.; Methodology, K.G.D., S.T.N., M.M.K. and J.C.; Project Administration, S.T.N., M.M.K. and J.C.; Supervision, S.T.N., M.M.K. and J.C.; Writing—Original Draft, K.G.D.; Writing—Review and Editing, K.G.D., S.T.N., M.M.K. and J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Human Research Ethics Committee (HREC) of the University of Hong Kong Ref. No.: EA210475 on 23 November 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are not publicly available due to privacy or ethical restrictions and will be available upon reasonable request from the corresponding author.

Acknowledgments: The authors would like to acknowledge the Environment and Ecology Bureau of the Hong Kong Special Administrative Region Government for financially supporting this study through the Green Tech Fund (grant No.: GTF202110158). This paper also constitutes an output

of part of a PhD research study carried out under the Hong Kong PhD Fellowship Scheme (No.: PF19-39440) of the HKSAR Government Research Grants Council. The authors also thank all the respondents who participated in the questionnaire survey for volunteering their time and effort to make this study possible.

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

Abbreviations

The following abbreviations are used in this manuscript:

BoL	Beginning of Life
BAMB	Buildings as Material Banks
BCI	Building Construction Industry
CE	Circular Economy
CDW	Construction and Demolition Waste
CDWM	Construction and Demolition Waste Management
CVC	Construction Value Chain
CW	Construction Waste
DfC	Design for Circularity
DfCMA	Design for Circular Manufacturing and Assembly
DfMA	Design for Manufacturing and Assembly
EoL	End of Life
EFA	Exploratory Factor Analysis
FSE	Fuzzy Synthetic Evaluation
GIS	Geographic Information System
IC	Industrialised Construction
IFD	Industrialised, Flexible and Demountable
KMO	Kaiser–Meyer–Olkin
LC	Lean Construction
MF	Membership Function
MiC	Modular Integrated Construction
PPVC	Prefabricated Prefinished Volumetric Construction
S-W	Shapiro–Wilk
WLC	Whole Life Cycle

References

1. Giorgi, S.; Lavagna, M.; Campioli, A. Circular economy and regeneration of building stock: Policy improvements, stakeholder networking and life cycle tools. In *Regeneration of the Built Environment from a Circular Economy Perspective*; Della Torre, S., Cattaneo, S., Lenzi, C., Zanelli, A., Eds.; Springer: Cham, Switzerland, 2020.
2. Iyer-Raniga, U.; Huovila, P. *Global State of Play for Circular Built Environment*; United Nations One Planet Network Sustainable Buildings and Construction Programme: Nairobi, Kenya, 2021.
3. United Nations Environment Programme. *2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme (UNEP): Nairobi, Kenya, 2020.
4. Sharma, N.; Kalbar, P.P.; Salman, M. Global review of circular economy and life cycle thinking in building Demolition Waste Management: A way ahead for India. *Build. Environ.* **2022**, *222*, 109413. [[CrossRef](#)]
5. Ding, Z.; Sun, Z.; Liu, R.; Xu, X. Evaluating the effects of policies on building construction waste management: A hybrid dynamic approach. *Environ. Sci. Pollut. Res.* **2023**, *30*, 67378–67397. [[CrossRef](#)]
6. Wuni, I.Y.; Shen, G.Q. Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. *Sustain. Prod. Consum.* **2022**, *29*, 574–587. [[CrossRef](#)]
7. Jaillon, L.; Poon, C.S. Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Autom. Constr.* **2014**, *39*, 195–202. [[CrossRef](#)]
8. Bianchi, M.; Cordella, M. Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade. *Ecol. Econ.* **2023**, *203*, 107607. [[CrossRef](#)]

9. Mesa, J.A.; Esparragoza, I.; Maury, H. Trends and Perspectives of Sustainable Product Design for Open Architecture Products: Facing the Circular Economy Model. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2019**, *6*, 377–391. [\[CrossRef\]](#)
10. Nuñez-Cacho, P.; Górecki, J.; Molina-Moreno, V.; Corpas-Iglesias, F.A. What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. *Sustainability* **2018**, *10*, 2340. [\[CrossRef\]](#)
11. Zairul, M. The recent trends on prefabricated buildings with circular economy (CE) approach. *Clean. Eng. Technol.* **2021**, *4*, 100239. [\[CrossRef\]](#)
12. Askar, R.; Bragança, L.; Gervásio, H. Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings. *Appl. Syst. Innov.* **2022**, *5*, 24. [\[CrossRef\]](#)
13. Sharp, J.; Hobbs, G. *BAMB Framework for Policies, Regulations and Standards*; European Union’s Horizon 2020 Research and Innovation Programme: Nairobi, Kenya, 2019.
14. Marsh, A.T.M.; Velenturf, A.P.M.; Bernal, S.A. Circular Economy strategies for concrete: Implementation and integration. *J. Clean. Prod.* **2022**, *362*, 132486. [\[CrossRef\]](#)
15. Eissa, R.; El-adaway, I.H. Accelerating the Circular Economy Transition: A Construction Value Chain-Structured Portfolio of Strategies and Implementation Insights. *J. Constr. Eng. Manag.* **2024**, *150*, 04024077. [\[CrossRef\]](#)
16. Chen, Q.; Feng, H.; Garcia de Soto, B. Revamping construction supply chain processes with circular economy strategies: A systematic literature review. *J. Clean. Prod.* **2022**, *335*, 130240. [\[CrossRef\]](#)
17. Oluleye, B.I.; Chan, D.W.M.; Antwi-Afari, P.; Olawumi, T.O. Modeling the principal success factors for attaining systemic circularity in the building construction industry: An international survey of circular economy experts. *Sustain. Prod. Consum.* **2023**, *37*, 268–283. [\[CrossRef\]](#)
18. Satola, D.; Kristiansen, A.B.; Houlihan-Wiberg, A.; Gustavsen, A.; Ma, T.; Wang, R.Z. Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study. *Build. Environ.* **2020**, *186*, 107358. [\[CrossRef\]](#)
19. Dewagoda, K.G.; Ng, S.T.; Chen, J. Driving systematic circular economy implementation in the construction industry: A construction value chain perspective. *J. Clean. Prod.* **2022**, *381*, 135197. [\[CrossRef\]](#)
20. Dewagoda, K.G.; Ng, S.T.; Kumaraswamy, M.M.; Chen, J. Design for Circular Manufacturing and Assembly (DfCMA): Synergising Circularity and Modularity in the Building Construction Industry. *Sustainability* **2024**, *16*, 9192. [\[CrossRef\]](#)
21. Leising, E.; Quist, J.; Bocken, N. Circular Economy in the building sector: Three cases and a collaboration tool. *J. Clean. Prod.* **2018**, *176*, 976–989. [\[CrossRef\]](#)
22. Wong, R.W.M.; Loo, B.P.Y. Sustainability implications of using precast concrete in construction: An in-depth project-level analysis spanning two decades. *J. Clean. Prod.* **2022**, *378*, 134486. [\[CrossRef\]](#)
23. 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. [\[CrossRef\]](#)
24. Nguyen, T.D.H.N.; Moon, H.; Ahn, Y. Critical Review of Trends in Modular Integrated Construction Research with a Focus on Sustainability. *Sustainability* **2022**, *14*, 12282. [\[CrossRef\]](#)
25. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1171–1183. [\[CrossRef\]](#)
26. Kyrö, R.; Jylhä, T.; Peltokorpi, A. Embodying circularity through usable relocatable modular buildings. *Facilities* **2019**, *37*, 75–90. [\[CrossRef\]](#)
27. Rankohi, S.; Carlo, C.; Iordanova, I.; Bourgault, M. Design-for-Manufacturing-and-Assembly (DfMA) for the construction industry: A review. In Proceedings of the 2022 Modular and Offsite Construction (MOC) Summit, Edmonton, AB, Canada, 27–29 July 2022.
28. Li, Z.; Shen, G.Q.; Xue, X. Critical review of the research on the management of prefabricated construction. *Habitat Int.* **2014**, *43*, 240–249. [\[CrossRef\]](#)
29. Wasim, M.; Han, T.M.; Huang, H.; Madiyev, M.; Ngo, T.D. An approach for sustainable, cost-effective and optimised material design for the prefabricated non-structural components of residential buildings. *J. Build. Eng.* **2020**, *32*, 101474. [\[CrossRef\]](#)
30. Abdelmageed, S.; Zayed, T. A study of literature in modular integrated construction—Critical review and future directions. *J. Clean. Prod.* **2020**, *277*, 124044. [\[CrossRef\]](#)
31. Langston, C.; Zhang, W. DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia. *Sustainability* **2021**, *13*, 9219. [\[CrossRef\]](#)
32. Montazeri, S.; Lei, Z.; Odo, N. Design for Manufacturing and Assembly (DfMA) in Construction: A Holistic Review of Current Trends and Future Directions. *Buildings* **2024**, *14*, 285. [\[CrossRef\]](#)
33. Benachio, G.L.F.; Freitas, M.D.C.D.; Tavares, S.F. Interactions between Lean Construction Principles and Circular Economy Practices for the Construction Industry. *J. Constr. Eng. Manag.* **2021**, *147*, 04021068. [\[CrossRef\]](#)
34. Obi, L.; Arif, M.; Daniel, E.I.; Oladinrin, O.T.; Goulding, J.S. Establishing underpinning concepts for integrating circular economy and offsite construction: A bibliometric review. *Built Environ. Proj. Asset Manag.* **2023**, *13*, 123–139. [\[CrossRef\]](#)

35. Kedir, F.; Hall, D.M. Resource efficiency in industrialized housing construction—A systematic review of current performance and future opportunities. *J. Clean. Prod.* **2021**, *286*, 125443. [[CrossRef](#)]
36. Dewagoda, K.G.; Kumaraswamy, M.M.; Chen, J.; Ng, S.T.; Jayathunga, T. Developing a Circular Economy Checklist for Designing Modular Buildings: A Case Study in Sri Lanka. In Proceedings of the CIB World Building Congress 2025, West Lafayette, IN, USA, 19–23 May 2025.
37. Dewagoda, K.G.; Ng, S.T.; Kumaraswamy, M.M. Design for Circularity: The Case of the Building Construction Industry. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1101*, 062026. [[CrossRef](#)]
38. Dewagoda, K.G.; Ng, S.T.; Kumaraswamy, M.M.; Chen, J. Understanding and readiness of the building construction industry in designing for circularity: A comparison with manufacturing industries. In Proceedings of the AUBEA2023 Conference, Auckland, New Zealand, 26–28 November 2023; pp. 281–293.
39. Pomponi, F.; Moncaster, A. Circular economy for the built environment: A research framework. *J. Clean. Prod.* **2017**, *143*, 710–718. [[CrossRef](#)]
40. Ekanayake, E.M.A.C.; Shen, G.Q.; Kumaraswamy, M.; Owusu, E.K. Critical supply chain vulnerabilities affecting supply chain resilience of industrialized construction in Hong Kong. *Eng. Constr. Archit. Manag.* **2021**, *28*, 3041–3059. [[CrossRef](#)]
41. Ekanayake, E.M.A.C.; Shen, G.; Kumaraswamy, M.; Owusu, E.K. A fuzzy synthetic evaluation of vulnerabilities affecting supply chain resilience of industrialized construction in Hong Kong. *Eng. Constr. Archit. Manag.* **2022**, *29*, 2358–2381. [[CrossRef](#)]
42. Van Teijlingen, E.; Hundley, V. The importance of pilot studies. *Soc. Res. Update* **2002**, *16*, 33. [[CrossRef](#)]
43. Brown, J.D. Statistics Corner: Questions and answers about language testing statistics: The Cronbach alpha reliability estimate. *JALT Test. Eval. SIG Newsl.* **2002**, *6*, 17–19.
44. Cronbach, L.J. Coefficient Alpha and the Internal Structure of Tests. *Psychometrika* **1951**, *16*, 297–334. [[CrossRef](#)]
45. Shapiro, S.S.; Wilk, M.B. An analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. [[CrossRef](#)]
46. Chou, Y.-M.; Polansky, A.M.; Mason, R.L. Transforming Non-Normal Data to Normality in Statistical Process Control. *J. Qual. Technol.* **1998**, *30*, 133–141. [[CrossRef](#)]
47. Shapiro, S.S.; Wilk, M.B.; Chen, H.J. A Comparative Study of Various Tests for Normality. *J. Am. Stat. Assoc.* **1968**, *63*, 1343–1372. [[CrossRef](#)]
48. Pett, M.A.; Lackey, N.R.; Sullivan, J.J. *Making Sense of Factor Analysis: The Use of Factor Analysis for Instrument Development in Health Care Research*; Sage: Thousand Oaks, CA, USA, 2003.
49. Kaiser, H.F. An index of factorial simplicity. *Psychometrika* **1974**, *39*, 31–36. [[CrossRef](#)]
50. Bartlett, M.S. Properties of sufficiency and statistical tests. *Proc. R. Soc. London. Ser. A-Math. Phys. Sci.* **1937**, *160*, 268–282. [[CrossRef](#)]
51. Kaiser, H.F.; Rice, J. Little Jiffy, Mark Iv. *Educ. Psychol. Meas.* **1974**, *34*, 111–117. [[CrossRef](#)]
52. Howard, M.C. A Review of Exploratory Factor Analysis Decisions and Overview of Current Practices: What We Are Doing and How Can We Improve? *Int. J. Hum.-Comput. Interact.* **2016**, *32*, 51–62. [[CrossRef](#)]
53. Deng, B.; Lv, X.; Du, Y.; Li, X.; Yin, Y. Critical risk factors for construction supply chain in China: A fuzzy synthetic evaluation analysis. *Eng. Constr. Archit. Manag.* **2025**, *32*, 483–506. [[CrossRef](#)]
54. Xu, Y.; Yeung, J.F.Y.; Chan, A.P.C.; Chan, D.W.M.; Wang, S.Q.; Ke, Y. Developing a risk assessment model for PPP projects in China—A fuzzy synthetic evaluation approach. *Autom. Constr.* **2010**, *19*, 929–943. [[CrossRef](#)]
55. Chang, N.-B.; Chen, H.W.; Ning, S.K. Identification of river water quality using the Fuzzy Synthetic Evaluation approach. *J. Environ. Manag.* **2001**, *63*, 293–305. [[CrossRef](#)] [[PubMed](#)]
56. Ali, A.H.; Kineber, A.F.; Qaralleh, T.J.O.; Alaboud, N.S.; Daoud, A.O. Classifying and evaluating enablers influencing modular construction utilization in the construction sector: A fuzzy synthetic evaluation. *Alex. Eng. J.* **2023**, *78*, 45–55. [[CrossRef](#)]
57. Omer Mazen, M.; Rahman Rahimi, A.; Almutairi, S. Strategies for Enhancing Construction Waste Recycling: A Fuzzy Synthetic Evaluation. In *Construction Research Congress 2022*; ASCE: Reston, VA, USA, 2022; pp. 676–685.
58. Shams, D.S.; Alkhalifa, F. Using Fuzzy Synthetic Evaluation (FSE) to assess the sustainability of New Educational Building Designs (NEBDs). *Eng. Constr. Archit. Manag.* **2025**, *ahead-of-print*. [[CrossRef](#)]
59. Thach, T.N.; Nguyen, M.V.; Khanh, H.D.; Phan, C.T.; Ahn, Y. Toward sustainable development: An assessment of the performance of green construction sites using fuzzy synthetic evaluation. *Eng. Constr. Archit. Manag.* **2025**, *ahead-of-print*. [[CrossRef](#)]
60. Ababio, B.K.; Lu, W. Modeling the determinants of circular procurement adoption for sustainable construction: A fuzzy logic-based evaluation approach. *Eng. Constr. Archit. Manag.* **2024**, *ahead-of-print*. [[CrossRef](#)]
61. Jung, S.; Yu, J. Design for Manufacturing and Assembly (DfMA) Checklists for Off-Site Construction (OSC) Projects. *Sustainability* **2022**, *14*, 11988. [[CrossRef](#)]
62. Chen, K.; Lu, W. Design for Manufacture and Assembly Oriented Design Approach to a Curtain Wall System: A Case Study of a Commercial Building in Wuhan, China. *Sustainability* **2018**, *10*, 2211. [[CrossRef](#)]
63. Gao, S.; Jin, R.; Lu, W. Design for manufacture and assembly in construction: A review. *Build. Res. Inf.* **2020**, *48*, 538–550. [[CrossRef](#)]

64. Rahla, K.M.; Mateus, R.; Bragança, L. Implementing Circular Economy Strategies in Buildings—From Theory to Practice. *Appl. Syst. Innov.* **2021**, *4*, 26. [\[CrossRef\]](#)
65. Dokter, G.; Thuvander, L.; Rahe, U. How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy. *Sustain. Prod. Consum.* **2021**, *26*, 692–708. [\[CrossRef\]](#)
66. Antwi-Afari, P.; Ng, S.T.; Chen, J.; Oluleye, B.I.; Antwi-Afari, M.F.; Ababio, B.K. Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. *Build. Environ.* **2023**, *239*, 110411. [\[CrossRef\]](#)
67. Durmisevic, E. *BAMB Reversible Building Design Guidelines and Protocol*; European Union's Horizon 2020 Research and Innovation Programme: Nairobi, Kenya, 2018.
68. Geldermans, R.J. Design for Change and Circularity—Accommodating Circular Material & Product Flows in Construction. *Energy Procedia* **2016**, *96*, 301–311. [\[CrossRef\]](#)
69. Pan, W.; Zhang, Z. Benchmarking the sustainability of concrete and steel modular construction for buildings in urban development. *Sustain. Cities Soc.* **2023**, *90*, 104400. [\[CrossRef\]](#)
70. Roxas, C.L.C.; Bautista, C.R.; Dela Cruz, O.G.; Dela Cruz, R.L.C.; De Pedro, J.P.Q.; Dungca, J.R.; Lejano, B.A.; Ongpeng, J.M.C. Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. *Buildings* **2023**, *13*, 1164. [\[CrossRef\]](#)
71. Lu, W.; Tan, T.; Xu, J.; Wang, J.; Chen, K.; Gao, S.; Xue, F. Design for manufacture and assembly (DfMA) in construction: The old and the new. *Archit. Eng. Des. Manag.* **2021**, *17*, 77–91. [\[CrossRef\]](#)
72. Royal Institute of British Architects. *DfMA Overlay to the RIBA Plan of Work*; RIBA Publishing: London, UK, 2021.
73. Bao, Z.; Laovisutthichai, V.; Tan, T.; Wang, Q.; Lu, W. Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction. *Build. Res. Inf.* **2022**, *50*, 325–338. [\[CrossRef\]](#)
74. Hyun, H.; Kim, H.-G.; Kim, J.-S. Integrated Off-Site Construction Design Process including DfMA Considerations. *Sustainability* **2022**, *14*, 4084. [\[CrossRef\]](#)
75. Van Stijn, A.; Gruis, V. Towards a circular built environment. *Smart Sustain. Built Environ.* **2020**, *9*, 635–653. [\[CrossRef\]](#)
76. Machado, N.; Morioka, S.N. Contributions of modularity to the circular economy: A systematic review of literature. *J. Build. Eng.* **2021**, *44*, 103322. [\[CrossRef\]](#)
77. Sonego, M.; Echeveste, M.E.S.; Galvan Debarba, H. The role of modularity in sustainable design: A systematic review. *J. Clean. Prod.* **2018**, *176*, 196–209. [\[CrossRef\]](#)
78. Building and Construction Authority. *Prefabricated Pre-Finished Volumetric Construction (PPVC) Guidebook*; Building and Construction Authority: Singapore, 2017.
79. Tan, T.; Lu, W.; Tan, G.; Xue, F.; Chen, K.; Xu, J.; Wang, J.; Gao, S. Construction-Oriented Design for Manufacture and Assembly Guidelines. *J. Constr. Eng. Manag.* **2020**, *146*, 04020085. [\[CrossRef\]](#)
80. Pasquire, C.L.; Connolly, G.E. Design for manufacture and assembly. In Proceedings of the 11th Annual Conference of the International Group for Lean Construction, Blacksburg, VA, USA, 22–24 July 2003; pp. 184–194.
81. Abd Razak, M.I.; Khoiry, M.A.; Wan Badaruzzaman, W.H.; Hussain, A.H. DfMA for a Better Industrialised Building System. *Buildings* **2022**, *12*, 794. [\[CrossRef\]](#)
82. Corfar, D.-A.; Tsavdaridis, K.D. A comprehensive review and classification of inter-module connections for hot-rolled steel modular building systems. *J. Build. Eng.* **2022**, *50*, 104006. [\[CrossRef\]](#)
83. Çetin, S.; Kirchherr, J. The Build Back Circular Framework: Circular Economy Strategies for Post-Disaster Reconstruction and Recovery. *Circ. Econ. Sustain.* **2025**, *5*, 1689–1726. [\[CrossRef\]](#)
84. Çetin, S.; De Wolf, C.; Bocken, N. Circular Digital Built Environment: An Emerging Framework. *Sustainability* **2021**, *13*, 6348. [\[CrossRef\]](#)
85. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L.; Colling, M. Strategies for Applying the Circular Economy to Prefabricated Buildings. *Buildings* **2018**, *8*, 125. [\[CrossRef\]](#)
86. Hossain, M.U.; Ng, S.T.; Antwi-Afari, P.; Amor, B. Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109948. [\[CrossRef\]](#)
87. Rajaratnam, D.; Stewart, R.A.; Liu, T.; Vieira, A.S. Building stock mining for a circular economy: A systematic review on application of GIS and remote sensing. *Resour. Conserv. Recycl. Adv.* **2023**, *18*, 200144. [\[CrossRef\]](#)
88. Li, J.; Ng, S.T.; Skitmore, M. Review of low-carbon refurbishment solutions for residential buildings with particular reference to multi-story buildings in Hong Kong. *Renew. Sustain. Energy Rev.* **2017**, *73*, 393–407. [\[CrossRef\]](#)
89. Grussing, M.N.; Liu, L.Y. Knowledge-Based Optimization of Building Maintenance, Repair, and Renovation Activities to Improve Facility Life Cycle Investments. *J. Perform. Constr. Facil.* **2014**, *28*, 539–548. [\[CrossRef\]](#)
90. 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**, *588*, 052027. [\[CrossRef\]](#)

91. Weerasinghe, L.N.K.; Darko, A.; Chan, A.P.C. Renewable Energy or Energy Efficiency? Building Occupant Preferences toward Net Zero Carbon Retrofit Measures. In Proceedings of the CIB World Building Congress 2025, West Lafayette, IN, USA, 19–23 May 2025; Purdue University: West Lafayette, IN, USA, 2025.
92. Madushika, U.G.D.; Lu, W. Modelling the driving forces of green retrofitting adoption in developing nations: A data-driven approach. *J. Build. Eng.* **2025**, *108*, 112921. [[CrossRef](#)]
93. Peiris, S.; Lai, J.H.K.; Kumaraswamy, M.M. Smart retrofitting for office buildings: Comparison of decision-making criteria between developing and developed regions. *J. Build. Eng.* **2024**, *97*, 110957. [[CrossRef](#)]
94. Jayawardana, J.; Sandanayake, M.; Kulatunga, A.K.; Jayasinghe, J.A.S.C.; Zhang, G.; Osadith, S.A.U. Evaluating the Circular Economy Potential of Modular Construction in Developing Economies—A Life Cycle Assessment. *Sustainability* **2023**, *15*, 16336. [[CrossRef](#)]
95. 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](#)]
96. Santos, P.; Cervantes, G.C.; Zaragoza-Benzal, A.; Byrne, A.; Karaca, F.; Ferrández, D.; Salles, A.; Bragança, L. Circular Material Usage Strategies and Principles in Buildings: A Review. *Buildings* **2024**, *14*, 281. [[CrossRef](#)]
97. Amarasinghe, I.; Liu, T.; Stewart, R.A.; Mostafa, S. Paving the way for lowering embodied carbon emissions in the building and construction sector. *Clean Technol. Environ. Policy* **2025**, *27*, 1825–1843. [[CrossRef](#)]
98. Tennakoon, G.A.; Rameezdeen, R.; Chileshe, N. Walking the talk towards sustainable consumption: Interventions to promote the uptake of reprocessed construction materials. *Eng. Constr. Archit. Manag.* **2024**, *31*, 2878–2899. [[CrossRef](#)]
99. Wijewickrama, M.K.C.S.; Chileshe, N.; Rameezdeen, R.; Ochoa, J.J. The Role of Government towards a Circular Economy in the Construction Industry: A Systematic Literature Review. In Proceedings of the 2nd World Conference on Waste Management, London, UK, 4–5 March 2021; pp. 9–22.
100. Laovisutthichai, V.; Lu, W.; Bao, Z. Design for construction waste minimization: Guidelines and practice. *Archit. Eng. Des. Manag.* **2022**, *18*, 279–298. [[CrossRef](#)]
101. Yang, Y.; Zheng, B.; Luk, C.; Yuen, K.-f.; Chan, A. Towards a sustainable circular economy: Understanding the environmental credits and loads of reusing modular building components from a multi-use cycle perspective. *Sustain. Prod. Consum.* **2024**, *46*, 543–558. [[CrossRef](#)]
102. Shandraseharan, A.; Rathnasinghe, A.; Sirimewan, D.; Thurairajah, N.; Thayaparan, M.; Waidyasekara, A. Developing Transformational Homes in Post-Disaster Reconstruction; A Transformative Space Perspective. In Proceedings of the 12th International Conference on Structural Engineering and Construction Management-2021, Kandy, Sri Lanka, 17–19 December 2021; pp. 182–189.
103. Bayazidi, E.; Jelodar, M.; Shahzad, W.; Kumar, V.; Shooshtarian, S. Integrating Circular Economy Principles in Construction: Comparing Product Data Templates, Material Passports, and Other Digital Tools. In Proceedings of the CIB World Building Congress (WBC2025), West Lafayette, IN, USA, 19–23 May 2025; Purdue University: West Lafayette, IN, USA, 2025.
104. Koskela, L. *An Exploration Towards a Production Theory and Its Application to Construction*; VTT Technical Research Centre of Finland: Espoo, Finland, 2000.
105. Stoll, H.W. Design for Manufacture: An Overview. *Appl. Mech. Rev.* **1986**, *39*, 1356–1364. [[CrossRef](#)]
106. Pan, W.; Hon, C.K. Briefing: Modular integrated construction for high-rise buildings. *Proc. Inst. Civ. Eng.—Munic. Eng.* **2020**, *173*, 64–68. [[CrossRef](#)]
107. Boothroyd, G.; Dewhurst, P.; Knight, W.A. *Product Design for Manufacture and Assembly*; CRC Press: Boca Raton, FL, USA, 2010.
108. Selvaraj, P.; Radhakrishnan, P.; Adithan, M. An integrated approach to design for manufacturing and assembly based on reduction of product development time and cost. *Int. J. Adv. Manuf. Technol.* **2009**, *42*, 13–29. [[CrossRef](#)]
109. Arup; Ellen MacArthur Foundation. *From Principles to Practices: First Steps Towards a Circular Built Environment*; Ellen MacArthur Foundation: Cowes, UK, 2018.
110. Nilsen, H.R. The hierarchy of resource use for a sustainable circular economy. *Int. J. Soc. Econ.* **2020**, *47*, 27–40. [[CrossRef](#)]
111. Cliff, N. The eigenvalues-greater-than-one rule and the reliability of components. *Psychol. Bull.* **1988**, *103*, 276–279. [[CrossRef](#)]
112. Silva, D.L.; Sabino, L.D.; Lanuza, D.M.; Adina, E.M.; Villaverde, B.S.; Pena, E.G. Silva’s management competency theory: A factor-item analytic approach utilizing oblique rotation direct oblmin method under Kaiser-Bartlett’s test of sphericity. In Proceedings of the World Congress on Engineering and Computer Science, San Francisco, CA, USA, 22–24 October 2014.
113. Hinkin, T.R. A Review of Scale Development Practices in the Study of Organizations. *J. Manag.* **1995**, *21*, 967–988. [[CrossRef](#)]
114. Bogue, R. Design for manufacture and assembly: Background, capabilities and applications. *Assem. Autom.* **2012**, *32*, 112–118. [[CrossRef](#)]
115. Jayasanka, T.A.D.K.; Darko, A.; Edwards, D.J.; Chan, A.P.C.; Jalaei, F. Automating building environmental assessment: A systematic review and future research directions. *Environ. Impact Assess. Rev.* **2024**, *106*, 107465. [[CrossRef](#)]
116. Jayakodi, S.; Senaratne, S.; Perera, S.; Bamdad, K. Circular economy assessment using project-level and organisation-level indicators for construction organisations: A systematic review. *Sustain. Prod. Consum.* **2024**, *48*, 324–338. [[CrossRef](#)]

117. Hendriks, N.A.; Vingerling, H. Industrial flexible and dismantable (IFD) building technology: A key to sustainable construction. In Proceedings of the International Symposium on Intergrated Life-Cycle Design of Materials and Structures, Helsinki, Finland, 22–24 May 2000; pp. 161–166.
118. Van Gassel, F. Experiences with the Design and Production of an Industrial, Flexible, and Demountable (IFD) Building System. In Proceedings of the 2002 19th ISARC, Washington, DC, USA, 23–25 September 2002; pp. 167–172.
119. Adabre, M.A.; Chan, A.P.C.; Darko, A.; Yang, Y.; Debrah, C. Institutional drivers for circular economy implementation in transitional housing: The case of Hong Kong. *Cities* **2025**, *164*, 106067. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.