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Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong

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Abstract

Circular construction practices and business models are considered essential to reduce the profound impact of the construction sector to the widening global circularity gap. However, practitioners and clients in Hong Kong have encountered profound challenges in integrating circular economy principles into modular construction projects. Therefore, this paper investigates the critical success factors for implementing circular modular construction projects. The research process comprised a focused literature review, consultation with subject matter experts, questionnaire survey of industry practitioners, mean score ranking, factor analysis, and fuzzy synthetic evaluation. The analyses revealed twenty-one significant success factors for integrating circular economy principles into modular construction projects in Hong Kong. The top five significant success factors include early design completion and freezing, early understanding and commitment of the client, effective leadership and support of a specialist contractor, adequate knowledge and experience of the project team, and collaborative working and information sharing among project teams. These underscored the significance of the planning and design stages for implementing circular modular construction projects successfully. Further analysis derived three clusters of the significant success factors: effective supply chain management, competence and early commitment, and collaboration and information management, explaining 61.461% of the total variance. A fuzzy synthetic evaluation showed that these three clusters significantly influence the success of circular modular construction projects. The paper provided practical and technical guidance on how to implement circular modular construction projects effectively. Therefore, this paper provides some important insights into the critical success factors for integrating circular economy objectives into circular modular construction projects.

Keywords: circularity; circular economy; circularity gap; circular modular construction; modular construction projects; Hong Kong

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1. Introduction

The global economy was 9.1% and 8.6% circular in 2019 and 2020, respectively (Circle Economy, 2020), highlighting a massive and expanding circularity gap. The worsening circularity gap demonstrates the persistence of the linear economy's take-make-dispose production and consumption tradition, which promotes high rates of resources extractions, unending material wastages, and low levels of end-of-use processing and cycling (Circle Economy, 2021, 2020). As the world continues to consume 100billion tonnes (Gt) of materials annually, the future outlook is grim because the global economy is breaching several severe milestones (Circle Economy, 2021).

The construction sector is one of the notorious villains in the widening circularity gap (United Nations Environment Programme, 2020). As a resource-intensive space, the construction sector has the largest ecological footprint. The processes and products of the dominant site-based construction techniques deplete a significant amount of virgin materials, consume excessive energy, emit prohibitive quantities of greenhouse gases, and generate significant quantities of solid landfill wastes (Cao et al., 2015; Monahan and Powell, 2011). The construction sector's wasteful nature and circularity gap are even pronounced in economies such as Hong Kong, with tremendous construction activities, where construction and demolition wastes account for over 25% of landfill waste (Environmental Protection Department, 2019).

Typically, business-as-usual in the construction industry embodies the linear economy (LE) model of materials production and consumption. Hence, the fundamental reason for the construction sector's massive circularity gap is the dominance of site-based construction techniques that operates based on the take-make-waste tradition of the LE (Kyrö et al., 2019; Norouzi et al., 2021). Hence, A circular approach to construction (i.e., circular construction) is considered a strategic path to reduce the sector's circularity gap. The construction sector is considered one with a high potential to implement circular economy (CE) strategies due to the discrete nature of construction processes and the growing adoption of eco-friendly products and technologies (Norouzi et al., 2021).

Hong Kong is promoting modular construction and CE to protect natural resources, improve the performance of construction projects, and reduce material wastage, solid wastes, and the environmental footprint of construction projects (Cao et al., 2015; Wuni and Shen, 2020a). CE reverses and reinvents the take-make-dispose tradition of LE to closed-loop material production and construction model, enabling the reuse and recycling of wastes and resources (Ellen MacArthur Foundation, 2021). Circular construction facilitates the reuse and recycling of building materials and maintains building components and resources at their highest intrinsic values for a more extended period. It enables building components to be kept in a continuous loop of use, reuse, repair, and recycle (van den Berg, 2019). Thus, it reduces construction waste and negative externalities such as CO_2 emissions (Akhimien et al., 2021).

As circular construction requires incorporating circularity principles into buildings' design, construction, and deconstruction, the modular construction approach provides a unique path to implement CE principles effectively (Kyrö et al., 2019). Modular construction constitutes a cleaner construction method whereby free-standing integrated volumetric building components (i.e., modules) are completed with finishes, fixtures, and fittings in an offsite factory environment and then transported to a construction site for installation (Development Bureau, 2020).

Circular modular construction projects (MCPs) are modular building projects designed, managed, and constructed based on CE principles (Kyrö et al., 2019). The design and construction of circular MCPs promote sustainable material usage, maximize material recovery, and avoid unnecessary waste generation disposed to landfills. Circular MCPs design waste and pollution out of the construction process, create a circular loop in material usage, reduce the ecological footprint, and protect the site and surrounding ecosystems (Ellen MacArthur Foundation, 2021). As such circular MCPs offer tremendous opportunities to preserve and enhance natural capital, optimize renewable resources, design out waste, and allow construction materials, products, and components to remain repetitive loops, maintaining them at their highest possible intrinsic value.

According to the Ellen MacArthur Foundation (2021), circular business models, circular design, reverse logistics, and enablers and favourable conditions (i.e., public policy) are required to achieve CE. However, prevailing industry discussions and the literature have focused mainly of circular designs and policy enablers. Without addressing circular business models and new engineering processes, construction organizations, practitioners, and clients in Hong Kong and elsewhere have encountered tremendous challenging in converting the neat theory of CE into replicable practice in MCPs. As both CE and modular construction are relatively new in Hong Kong and globally, there is currently no recipe for success due to the limited knowledge of how best to integrate CE principles in MCPs. Therefore, the critical success factors (CSFs) for implementing circular MCPs remain a black box, an important research gap, and a Holy grail.

The CSFs concept constitutes a robust management support tool that can reveal the few essential practices in which satisfactory results will ensure the success of circular modular construction projects (Zwikael and Globerson, 2006). Therefore, this paper aims to develop CSFs for managing circular MCPs in Hong Kong, with two specific objectives: (i) to identify and prioritize CSFs for managing circular MCPs and (ii) to categorize and model the impact of various CSFs for managing MCPs in Hong Kong. The study's main contribution lies in providing a better insight into how best to manage circular MCPs. It has established the first set of CSFs for integrating CE principles into MCPs.

2. Literature review

2.1 Overview of circular modular construction projects

Circular modular construction integrates CE principles into the objectives of modular construction. Thus, it is a sustainable construction process in which value-added modules are deliberately designed and manufactured in an offsite factory and then transported to the construction site for installation to enable the building materials to maintain a cyclic loop of construction, use, deconstruction, reuse, recycle, and back to material for construction (Ellen MacArthur Foundation, 2021). At the very least, circular MCPs are designed, managed, constructed, and operated with the objectives of reducing, reusing, and recycling materials and building components (Kyrö et al., 2019).

Circular MCPs are considered the best sustainable construction projects because they decouple construction lifecycles from finite consumption of materials through designing waste-free buildings (Norouzi et al., 2021). Advanced circular MCPs adopt restorative and regenerative construction processes based on the principles of designing out pollution and wastes, creating a circular loop in material usage, using circular construction materials, and integrating project-level ecological civilization principles to preserve ecosystems (Cao et al., 2015; Ellen MacArthur Foundation, 2021). The most fundamental unique aspect of circular MCPs is the design decisions. A circular MCP design facilitates the reuse, deconstruction, and recycling of building components and construction materials. Thus, a successful circular MCP design requires carefully selecting materials, standardized components, and blueprint specifications that enable end-of-life sorting, separation, or reuse of building components and materials. The design must consider longer economic life, deconstruction, zero-waste, and possible valuable applications of by-products and wastes.

Circular MCPs have generated 46 – 87% onsite construction waste reduction (Pan et al., 2020), 84.7% reduced materials expenditure (Tam et al., 2007), 35.82% reduced resources depletion, 3.47% reduced ecosystem damage (Cao et al., 2015), 15.6% and 3.2% reduced embodied, and operational carbon emissions, respectively (Quale et al., 2012), 60 – 68% reduced onsite energy consumption, 66 – 70% reduced water consumption, 7 – 10 % reduced noise pollution, and 25 – 50% reduced air pollution (Pan et al., 2020). Therefore, circular MCPs can significantly reduce the construction sector's environmental impact and ecological footprint while providing value-for-money and cost savings to project stakeholders.

2.2 Critical success factors for circular modular construction projects

There is scarce literature explicitly addressing the CSFs for managing and implementing circular MCPs. However, there is considerable documentation of CSFs for CE in construction and MCPs applicable to circular MCPs. For instance, Norouzi et al. (2021) documented that a successful circular MCP requires effective collaboration and inputs from various stakeholders in the supply chain because each echelon contributes to materials depletion, environmental impacts, and cost of the building production. Similarly, Wuni and Shen (2020b) indicated that an integrated procurement system and contracting strategy are required to encourage the collaborative design and construction of circular MCPs. The integrated approaches facilitate the integration of stakeholders throughout the circular MCP delivery process (Nawi et al., 2012). García et al. (2017) corroborated that stakeholders and project participants must be prepared to have repetitive and multiple system coordination meetings to integrate offsite and onsite construction details and work packages seamlessly.

Repetitive project teams within integrated project delivery methods such as design-build can improve circular MCPs (Kamar et al., 2014). This delivery mode can avoid disruptions in module transport and crane logistics because introducing new project members without the appropriate competencies can derail the performance of circular MCPs (Building and Construction Authority, 2017). The circular MCP team must accept that the installing construction manager controls the project delivery process regardless of team structure or contract strategy. Though the client can establish a separate contract with designers, the construction manager as the chief facilitator and coordinator of the circular MCP must understand the terms and details of the contract to coordinate all activities, processes, and teams from design to installation (Wuni et al., 2021).

As the factory production stage constitutes a significant driver cost and waste, it is critical to allow factory input into the design for manufacture, assembly, and circularity (Wuni et al., 2021). It is instructive to allow subcontractors, particularly component manufacturers, to collaborate with the design team and provide input into the design. The production engineers better understand module manufacturing constraints and interfacing or connections between the components. Hence, their early involvement can proactively avoid intractable factory production and onsite assembly challenges (Wuni et al., 2021). This practice also demands a supportive procurement process that encourages deep and formal design assistance.

Kyrö et al. (2019) found that relevant bespoke guidelines, standards, and policy interventions are required to regulate the inclusion of CE principles into the design, construction, and deconstruction of MCPs. It is also considered essential to complete and freeze the design early to realize the benefits of circular MCPs (Choi et al., 2016; O'Connor et al., 2014). Hard design freezes and minor changes are required early because the modules cannot be manufactured without the statutory approval of the building plans (Li et al., 2018). An accurate and detailed design specification is also paramount because changes are limited once the design is approved and frozen. The costs of late design changes in circular MCPs are prohibitive since additional time and resources will be required to implement the changes in the detailed design (Wuni and Shen, 2020b). Another relevant success factor is repetition in design elements (Kyrö et al., 2019). Repetition of design layout, structural system, and components not only facilitates the benefits of economies of scale but could significantly avoid materials wastage.

El-Abidi et al. (2019) and García et al. (2017) assessed the CSFs for implementing circular industrialized building systems. The studies identified relevant CSFs, including a selection of suitable procurement system and contracting strategy, clear and realistic project objectives, effective leadership of a specialist builder, effective risk management, advanced planning and scheduling, effective communication, suitable design, active client involvement, extensive supply chain coordination, use of competent project teams, and support of digital technologies. Kamar et al. (2014) established CSFs similar to those of El-Abidi et al. (2019) and García et al. (2017). The relevant CSFs were identified to include early commitment, good communication among project teams, competent project team, extensive planning and scheduling, detailed and accurate design specification, supply chain management, continuous improvement, and support of information technologies.

Choi et al. (2016) and O'Connor et al. (2014) concluded that early design completion and freezing, team commitment, adequate funding and resources, involvement of manufacturers, and effective risk management constitute the essential CSFs for improving the success of circular MCPs. Drawing on practitioners' opinions in China, Li et al. (2018) established that a competent design team, manufacturers' experience, effective leadership of project managers, and detailed design specifications constitute the top four CSFs for the planning and control of circular prefabricated construction projects. Through a review, Wuni and Shen (2020b) revealed relevant CSFs for managing circular modular integrated construction projects, including suitable design, suitable site, extensive planning, supply chain management, coordination of onsite and offsite construction details, competent factory inspection team, and inventory management.

The focused literature review presented above demonstrates that existing studies have done an excellent job discussing factors critical for managing circular MCPs. The literature spanned between 2014 and 2021, providing the opportunity to recruit a robust set of CSFs for managing MCPs. However, none explicitly assessed and prioritized the CSFs for managing circular MCPs in a context. The study draws on the existing evidence to evaluate and develop bespoke CSFs for managing circular MCPs in Hong Kong.

3. Methods

The study implemented a quantitative research design to develop CSFs for managing circular MCPs in Hong Kong. The research process comprised four major activities, including a focused literature review, consultation of experts, data collection, statistical pretesting of data, and data analysis. Fig. 1 is a flowchart of the research process, and various components are described next.

3.1 Developing potential critical success factors for circular modular construction projects

The study conducted a focused literature review to extract potential CSFs for implementing circular MCPs. Relevant articles were identified through search queries in Scopus and Web of Science. As presented in section 2.2, relevant articles were reviewed to recruit the relevant CSFs. A consultation was conducted with three industry practitioners with relevant knowledge of circular MCPs to refine and itemize the relevant CSFs applicable to circular MCPs in Hong Kong. The consultation was necessary because CSFs are contextually sensitive (Wuni and Shen, 2020b;

Zwikael and Globerson, 2006). Also, none of the reviewed studies explicitly and directly examined the identified CSFs in circular MCPs. Table 1 summarizes the relevant CSFs for managing circular MCPs identified from both the literature and refined through the expert consultation, which formed the basis of the evaluation in this study.

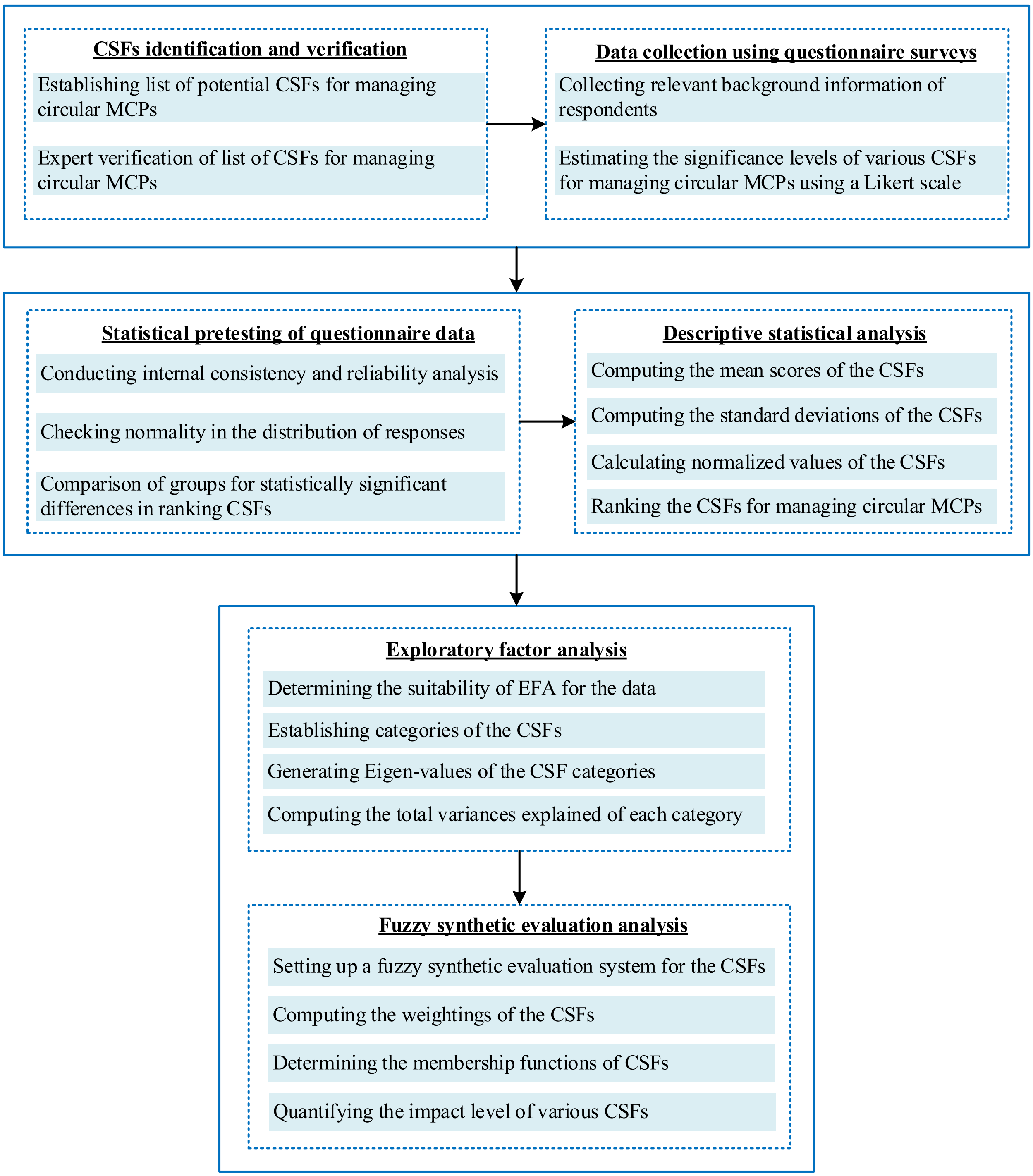

Fig. 1. Methodological framework of the study

Table 1. Verified list of critical success factors for circular modular construction projects

ID	Critical success factor
CSF1	Adequate knowledge and experience of the project team
CSF2	Early understanding and commitment of the client
CSF3	Effective leadership and support of a specialist contractor
CSF4	Collaborative working and information sharing among project teams
CSF5	Early design completion and freezing
CSF6	Suitable site characteristics and layout
CSF7	Design for manufacture, assembly, and circular economy
CSF8	Extensive upfront planning for circular modular construction projects
CSF9	Use of collaborative procurement system and contracting
CSF10	Integrating circular economy principles into the supply chain of modular construction projects
CSF11	Early and active involvement of critical project stakeholders
CSF12	Effective coordination and integration of stakeholders
CSF13	Leveraging information from demolition and design lifecycle stages
CSF14	Effective coordination of onsite and offsite work packages
CSF15	Using suitable structural system and construction material
CSF16	Effective use of building information modeling
CSF17	Effective management of critical tolerances between interfaces
CSF18	Early engagement of certification body for factory inspection
CSF19	Inventory management and control
CSF20	Use of just-in-time delivery arrangement
CSF21	Effective use of document management system
CSF22	Use of hedging strategies and transport delay avoidance
CSF23	Adequate lead time for the bespoke processes of circular modular construction projects

3.2 Questionnaire survey

A questionnaire survey was conducted to measure the significance of the identified CSFs for managing circular MCPs in Hong Kong. A questionnaire form (see Appendix I) with closed-ended questions was designed and piloted with the three industry practitioners who consulted on the relevant CSFs. Feedbacks from the pilot survey were used to improve the final questionnaire survey form. The form contained two sections. Section I solicited relevant information from the respondents. Section II asked the respondents to rate the significance of twenty-three CSFs for managing circular MCPs in Hong Kong on a 5-point rating scale, comprising 1(Very insignificant), 2(Insignificant), 3(Moderately significant), 4 (Significant), and 5(Very significant).

The target respondents were registered Hong Kong construction industry practitioners and experts with knowledge and experience in circular MCPs. The registered construction practitioners are those with certified qualifications and knowledge to deliver circular MCPs in Hong Kong. Thus, their opinions on the relative importance of the CSFs are valid and representative of real-world requirements of MCPs in Hong Kong. Contact details of five-hundred respondents were recruited from three large local databases of registered construction practitioners in Hong Kong: (i) The Architectural Services Department list of organizations, (ii) Engineering & Associated Consultants Selection Board list of consulting organizations, and (iii) Architectural and Associated Consultants Selection Board list of consulting organizations. Personalized invitation emails were sent to the respondents with soft copies of the questionnaire form, including an online link, and requested to verify their suitability and complete the survey. A total of 117 valid responses were received. Table 2 summarizes the demographic breakdown of the respondents.

Table 2. Relevant information of the Hong Kong respondents

Category	Attribute	Frequency (N=117)	Percentage (N=100%)
Institution of respondent	Consultancy	42	35.9
	Construction company	23	19.7
	Government agency	15	12.8
	Academic/Research Institution	9	7.7
	Developer	7	6.0
	Engineering firm	7	6.0
	Quantity Surveyor	5	4.3
	Architectural firm	3	2.6
	Supplier/Manufacturing firm	2	1.7
	Logistics company	1	0.9
	Professional institution	1	0.9
	Statutory Body	1	0.9

	Social Service Organization	1	0.9
Occupation of respondent	Director	45	38.5
	Project Manager	18	15.4
	Designer (Engineer/Architect)	18	15.4
	Quantity Surveyor	9	7.7
	Academic/Researcher	8	6.8
	Senior Manager	7	6
	Main Contractor	4	3.4
	Client	1	0.9
	Manufacturer/Supplier	1	0.9
	BIM Manager/Engineer	1	0.9
	Technical Supervisor	1	0.9
	Engineering Manager	1	0.9
	Maintenance Surveyor	1	0.9
	Assistant Manager	1	0.9
	Chief Executive Officer	1	0.9
Years of construction industry experience	1 - 5 years	15	12.8
	6 - 10 years	12	10.3
	11 - 15 years	5	4.3
	16 - 20 years	7	6
	Over 20 years	78	66.7
Years of experience in circular modular construction	1 year	48	41
	2 years	32	27.4
	3 years	20	17.1
	4 years	3	2.6
	Over 4 years	14	12

The practitioners worked in varied institutions involved in the delivery of circular MCPs in Hong Kong. The largest responses (77%) were provided by subject matter experts and practitioners working in consultancies, construction companies, government agencies, and academic/research institutions. Also, the respondents had diverse occupational and professional backgrounds, providing a good opportunity to incorporate rich and diverse opinions into the assessment of the CSFs. Most of the respondents were directors (38.5%), project managers (15.4%), designers/engineers/architects (15.4%), quantity surveyors (7.7%), academics/researchers (6.8%), senior managers (6.0%), and main contractors (3.4%) of circular MCPs in Hong Kong. These players and stakeholders make the crucial decisions that influence the success of circular MCPs.

Most of the respondents (77%) had at least 11 – 15 years of construction industry experience in Hong Kong, rendering them more qualified and appropriate to evaluate the success factors for circular MCPs in the context of Hong Kong. The respondents further had considerable years of experience in circular MCPs in Hong Kong.

3.3 Statistical pretesting of questionnaire survey data

The questionnaire survey data was coded and managed using the Statistical Package for the Social Sciences (SPSS v.26). To ensure uniformity, the study conducted all statistical pretesting at a 95% confidence interval (α = 0. 05). The Cronbach's Alpha was used to assess the internal consistency of the responses and reliability of the questionnaire.

The reliability analysis generated a Cronbach's Alpha of 0.948 for the 23 CSFs, indicating an excellent internal consistency in the assessment of the CSFs. The Shapiro – Wilk (S – W) test was conducted to ascertain normality in the data distribution, based on the null hypothesis that the sample is normally distributed (Chou et al., 1998). Also, the Kruskal – Wallis (K – W) test was conducted to ascertain whether there was a statistically significant disparity among the respondents in assessing the CSFs for circular MCPs due to their varied professional orientations (Ostertagová et al., 2014).

3.4 Descriptive statistical analysis of critical success factors for circular modular construction projects

Descriptive statistical techniques, including mean, standard deviation, and normalized mean, were used to quantify and rank the most significant CSFs for managing circular MCPs in Hong Kong. The mean scores (μ_i), standard deviation (σ_i), and normalized means scores ($N\mu_i$) were computed using Eqns. (1), (2), and (3), respectively.

$$\text{Mean score } (\mu_i) = \frac{\sum(X_i \text{ x } F_i)}{\text{N}} \quad (1)$$

$$\text{Standard deviation } (\sigma_i) = \sqrt{\frac{\sum(X_i - \mu_i)^2}{\text{N}}} \quad (2)$$

$$\text{Normalized mean score } (\text{N}\mu_i) = \frac{\mu_i - \text{Min}.\mu_i}{Max.\mu_i - Min.\mu_i} \quad (3)$$

where X_i denotes a score assigned to a CSF ranging from 1 to 5; F_i represents the frequency of each rating (i.e., 1 – 5) assigned to a CSF; Min.μ_i denotes the minimum mean score among the CSFs set; Max.μ_i represents the maximum mean score among the CSFs set; and N denotes the total number of responses a CSF obtained (i.e., sample size). The mean scores of the CSFs were interpreted as follows: μ_i <1.5 (Very insignificant), $1.5 \le \mu_i < 2.5$ (Insignificant), $2.5 \le \mu_i < 3.5$ (Moderately significant), $3.5 \le \mu_i < 4.5$ (Significant), and $\mu_i \ge 4.5$ (Very significant). As a thumb rule, a normalized mean score of 0.5 was considered a minimum significance threshold.

3.5 Exploratory factor analysis of critical success factors for managing circular modular construction projects

The suitability of the data for exploratory factor analysis (EFA) was tested using relevant statistical metrics, including sample size to CSF ratio, reliability score, anti-image correlation matrix, Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, and Bartlett's Test of Sphericity (BTS) (Pett et al., 2003). Drawing on the works of Wuni et al.(Wuni et al., 2021), Table 3 summarizes the metrics and their acceptable thresholds. The suitability test showed that the sample size to CSF ratio of 5:1 (117/23) met the minimum threshold for EFA (Lingard and Rowlinson, 2006). The Cronbach's Alpha of 0.948 exceeded the minimum threshold of 0.7 (Cronbach, 1951). The KMO test statistic of 0.924 was within an acceptable range (Wuni et al., 2021). BTS with a Pearson Chi-Square, $\chi^2 = 1702.516$ and $p < 0.000$, indicated that the correlation matrix of the CSFs varied significantly from an identity matrix.

Table 3. Statistical metrics for verifying the suitability of the data for exploratory factor analysis

Test statistic		Questionnaire data	Acceptable threshold
Sample size to critical success factor ratio		5: 1	≥ 5: 1
Cronbach's alpha		0.948	0.70 – 1.0
Anti-image correlation (coefficient) matrix		> 0.50	> 0.50
Kaiser-Meyer-Olkin measure of sampling adequacy		0.924	0.80 – 1.0
Bartlett's Test of Sphericity	Approx. χ^2	1702.516	N/A
	df	253	N/A
	Sig.	0.000	$p < 0.05$

The anti-image correlation coefficients between the CSFs met the acceptable threshold. The corroborating evidence demonstrated the suitability of the data for EFA. The study conducted the EFA using principal component analysis as the extraction method and Varimax with Kaiser Normalization as the extraction method. The rotation converged in 9 iterations and generated a 3-factor solution with eigenvalues greater than 1.0 and explaining about 61.461% of the variance of the CSFs for managing circular MCPs.

3.6 Fuzzy synthetic evaluation of critical success factors for managing circular modular construction projects

Fuzzy synthetic evaluation (FSE) constitutes a component of fuzzy set theory. It is regarded as an artificial intelligence technique that uses fuzzy logic to quantify the degree of truth in human judgment (Boussabaine, 2014). The embodied fuzzy logic enables FSE to overcome the inherent limitations of using the binary Boolean logic (i.e., Yes/No or True/False) to assess events. The imprecision and uncertainties associated with assigning significance levels to the various CSFs render FSE a good choice of evaluation technique. FSE was used to compute the significance indices of the CSFs for managing circular MCPs because it uses an advanced computational framework that integrates membership functions to manipulate and make an objective assessment of the subjectiveness, fuzziness, and imprecision associated with the assessment of the CSFs (Sadiq and Rodriguez, 2004). Drawing on well-established protocols (Xu et al., 2010), the FSE was completed in four steps.

3.6.1 Setting up the fuzzy synthetic evaluation index system

Step 1 of the FSE methodology involves setting up the FSE index system (Xu et al., 2010). The first-level evaluation index system for the three-factor groupings of the CSFs (hereafter, principal success factors, PSFs) was defined as U = (u_1, u_2, u_3), where u_1, u_2, and u_3 denotes PSF1, PSF2, and PSF3, respectively. The second level evaluation index system for the CSFs within each PSF was defined: as : u_1 = {u_{11}, u_{12}, u_{13},…, u_{1n}), u_2 = {u_{21}, u_{22}, u_{23},…, u_{2n}), and u_3 = {u_{31}, u_{32}, u_{33},…, u_{3n}); where n denotes the number of CSFs in u_1, u_2, and u_3. These index systems formed the input variables of the FSE process. The rating scale used the assess the significance of the CSFs was defined as V = {1, 2, 3, 4, 5}, reflecting the set of grade alternatives of the scale, comprising V_1(Very insignificant), V_2(Insignificant), V_3(Moderately significant), V_4(Significant), and V_5(Very significant).

3.6.2 Calculating the weightings of the critical and principal success factors

Step 2 of the FSE methodology involves computing the weighting (W) of the CSFs and PSFs. The normalized mean method was used to compute the weightings of each CSF and PSF using Eqn. (4) and expressed as Eqn. (5).

$$W_i = \frac{\mu_i}{\sum_{i=1}^{5} \mu_i}, \quad 0 \le W_i \le 1, \quad \Sigma\,(W_i) = 1 \tag{4}$$

$$W_s = \{w_1, w_2, w_3, \ldots, w_n\} \tag{5}$$

where μ_i denotes the mean score of a CSF or total mean score of a PSF; W_i denotes the weight of a CSF or PSF; W_s represents a set of weights for CSFs in a PSF; n denotes the number of CSFs in a PSF; and $\Sigma (W_i)$ denotes the summation of weightings.

3.6.3 Computing the membership function of the critical and principal success factors

Step 3 in FSE involve determining the membership function (MFs) of each CSF and PSF. The FSE technique uses the weights the experts assigned to each CSF to derive an MF of a CSF. The MF of a CSF (v_{in}) was determined using Eqn. (6).

$$MF_{v_{in}} = \frac{X_{1v_{in}}}{V_1} + \frac{X_{2v_{in}}}{V_2} + \frac{X_{3v_{in}}}{V_3} + \frac{X_{4v_{in}}}{V_4} + \frac{X_{5v_{in}}}{V_5} \quad (6)$$

where, $MF_{v_{in}}$ denotes the MF of a CSF v_{in}; $X_{j_{v_{in}}}$ (j = 1, 2, 3, 4, 5) represents the percentage of a score the respondents assigned to a CSF v_{in}; and $X_{j_{v_{in}}}/V_j$ explains the relation between $X_{j_{v_{in}}}$ and its associated grade alternative based on the rating scale. For example, 1.71%, 5.13%, 26.50%, 48.72%, and 17.95% of the respondents rated CSF10 (Integrating circular economy principles into the supply chain of modular construction projects) as "Very insignificant", "Insignificant", "Moderately significant", "Significant", and "Very significant", respectively. Hence, the MF of CSF was computed as follows:

$$MF_{CSF10} = \frac{0.02}{V_1} + \frac{0.05}{V_2} + \frac{0.26}{V_3} + \frac{0.49}{V_4} + \frac{0.18}{V_5} = (0.02, 0.05, 0.26, 0.49, 0.18).$$

However, the MF of a PSF is not determined straightforward. The MF of a PSF (D_i) is computed as a product of the fuzzy matrix of the MFs (R_i) of its CSFs and weighting function (Eqn. 5). Both R_i and D_i are determined using Eqns. (7) and (8), respectively.

$$R_i = \begin{bmatrix} MF_{v_{i1}} \\ MF_{v_{i2}} \\ MF_{v_{i3}} \\ \cdots \\ MF_{v_{in}} \end{bmatrix} = \begin{bmatrix} X_{1v_{i1}} & X_{2v_{i1}} & X_{3v_{i1}} & X_{4v_{i1}} & X_{5v_{i1}} \\ X_{1v_{i2}} & X_{2v_{i2}} & X_{3v_{i2}} & X_{4v_{i2}} & X_{5v_{i2}} \\ X_{1v_{i3}} & X_{2v_{i3}} & X_{3v_{i3}} & X_{4v_{i3}} & X_{5v_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ X_{1v_{in}} & X_{2v_{in}} & X_{3v_{in}} & X_{4v_{in}} & X_{5v_{in}} \end{bmatrix} \quad (7)$$

$$D_i = W_i \bullet R_i = (w_1, w_2, w_3, \ldots, w_n) \bullet \begin{bmatrix} X_{1v_{i1}} & X_{2v_{i1}} & X_{3v_{i1}} & X_{4v_{i1}} & X_{5v_{i1}} \\ X_{1v_{i2}} & X_{2v_{i2}} & X_{3v_{i2}} & X_{4v_{i2}} & X_{5v_{i2}} \\ X_{1v_{i3}} & X_{2v_{i3}} & X_{3v_{i3}} & X_{4v_{i3}} & X_{5v_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ X_{1v_{in}} & X_{2v_{in}} & X_{3v_{in}} & X_{4v_{in}} & X_{5v_{in}} \end{bmatrix} = (d_{i1}, d_{i2}, d_{i3}, \ldots, d_{in}) \quad (8)$$

Where"●" is a fuzzy composite operation and d_{in} denotes the degree of membership of the grade alternative for a CSF.

3.6.4 Quantifying the significance indices of the principal success factors

Step 4 involves quantifying the significance levels and indices of the PSFs. The significance index of each PSF is computed as a product of the fuzzy evaluation matrix (D_i) and the grade alternatives of the rating scale (V_i). The significance index of a PSF and the overall significance of the PSFs were computed using Eqn. (9).

$$\text{Significance Index} = \sum_{i=1}^{n}(D_i \times V_i) = (d_{i1}, d_{i2}, d_{i3}, d_{i4}, d_{i5}) \text{ x } (v_1, v_2, v_3, v_4, v_5)$$
$$= (d_{i1}{*}v_1) + (d_{i2}{*}v_2) + (d_{i3}{*}v_3) + (d_{i4}{*}v_4) + (d_{i5}{*}v_5) \quad (9)$$

4. Results and discussion

4.1 Significant critical success factors for managing circular modular construction projects in Hong Kong

Table 4 summarizes the normality test, the test of agreement, mean scores, standard deviation, normalized mean scores, and rankings of the 23 CSFs for managing circular MCPs in Hong Kong. The S – W test was significant at a 0.05 significance level for all CSFs, indicating the data was not normally distributed. The non-normality imposed non-parametric statistical techniques such as the K – W test to ascertain consensus among the respondents (Kim, 2015; Wuni et al., 2021). Except for CSF13, the K – W test was not significant at a 0.05 significance level for all CSFs, indicating the absence of statistically significant disparity among the respondents in assessing CSFs. However, there was no consensus among the independent groups of respondents in assessing CSF13. Ideally, CSF13 should be eliminated, or the data should be segregated into independent groups in further statistical analysis of CSF13. But since it was one item with a high mean score, the study considered it for further analysis. The consensus among the respondents and convergence of the responses for the 22 CSFs provided a statistical legitimacy to consider the data holistically for further analysis. Aside from CSF19 and CSF21, the CSFs obtained a mean score higher than 3.50, indicating that 21 CSFs were considered significant when managing circular MCPs in Hong Kong.

Further, the normalized mean scores revealed thirteen prominent CSFs for managing circular MCPs with values above the 0.5 significance threshold. Based on the mean and normalized mean scores, the top five significant CSFs for managing circular MCPs in Hong Kong include CSF5 (early design completion and freezing), CSF2 (early understanding and commitment of the client), CSF3 (Effective leadership and support of a specialist contractor), CSF1 (adequate knowledge and experience of the project team), and CSF4 (collaborative working and information sharing among project teams). These CSFs are discussed next.

Table 4. Statistical scores and ranking of the critical success factors for managing circular modular construction projects in Hong Kong

ID	CSF	S – W test (p-values)	K – W test (p-values)	μ_i	σ_i	$N\mu_i$	Rank
CSF1	Adequate knowledge and experience of the project team	0.00*	0.64	4.19	0.78	0.87	4
CSF2	Early understanding and commitment of the client	0.00*	0.28	4.23	0.76	0.91	2

CSF3	Effective leadership and support of a specialist contractor	0.00*	0.60	4.20	0.78	0.88	3
CSF4	Collaborative working and information sharing among project teams	0.00*	0.26	4.17	0.74	0.85	5
CSF5	Early design completion and freezing	0.00*	0.65	4.31	0.78	1.00	1
CSF6	Suitable site characteristics and layout	0.00*	0.37	3.79	0.78	0.44	16
CSF7	Design for manufacture, assembly, and circular economy	0.00*	0.36	4.08	0.84	0.75	6
CSF8	Extensive upfront planning for circular modular construction projects	0.00*	0.29	3.97	0.80	0.63	9
CSF9	Use of collaborative procurement system and contracting	0.00*	0.64	3.64	0.88	0.28	18
CSF10	Integrating circular economy principles into the supply chain of modular construction projects	0.00*	0.23	3.76	0.75	0.41	17
CSF11	Early and active involvement of critical project stakeholders	0.00*	0.67	4.05	0.84	0.72	7
CSF12	Effective coordination and integration of stakeholders	0.00*	0.45	3.98	0.74	0.65	8
CSF13	Leveraging information from demolition and design life-cycle stages	0.00*	0.03**	3.97	0.82	0.63	9
CSF14	Effective coordination of onsite and offsite work packages	0.00*	0.23	3.84	0.81	0.49	13
CSF15	Using suitable structural system and construction material	0.00*	0.90	3.97	0.84	0.63	9
CSF16	Effective use of building information modelling	0.00*	0.58	3.55	0.94	0.18	20
CSF17	Effective management of critical tolerances between interfaces	0.00*	0.75	3.91	0.76	0.57	12
CSF18	Early engagement of certification body for factory inspection	0.00*	0.62	3.64	0.91	0.28	18
CSF19	Inventory management and control	0.00*	0.41	3.44	0.77	0.06	22
CSF20	Use of just-in-time delivery arrangement	0.00*	0.34	3.81	0.86	0.46	15
CSF21	Effective use of document management system	0.00*	0.15	3.38	0.81	0.00	23
CSF22	Use of hedging strategies and transport delay avoidance	0.00*	0.78	3.51	0.81	0.14	21
CSF23	Adequate lead time for the bespoke processes of circular modular construction projects	0.00*	0.55	3.82	0.74	0.47	14

* The S – W test was significant at a 0.05 significance level. ** The K – W test was significant at a 0.05 significance level.

Obtaining the highest mean score of 4.31, early design completion and freezing constitute the most significant CSF for implementing circular MCPs in Hong Kong. Gibb and Isack (2003) considered early design freeze the most important practice to reap the full benefits of modular solutions in construction projects. Detailed design specification, owner's approval of the design, and early design freeze provide an adequate lead time for pre-production activities such as mock-up testing and prototyping. Early design completion enables a timely production of modules to shorten construction time (O'Connor et al., 2014). However, it is essential to incorporate the inputs of production engineers in the design to proactively resolve downstream factory production constraints before the detailed design hits the production line (Wuni et al., 2021).

Receiving a mean score of 4.23, early understanding and commitment of the client constitute the second most significant CSF for implementing circular MCPs in Hong Kong. Blismas (2007) identified early commitment as a significant CSFs for implementing MCPs in Australia. According to Hwang et al. (2018), CE and modular construction are inappropriate for certain construction project types. Thus, it is crucial to understand the suitability of circular modular construction for construction projects based on relevant data. Client's or owner's early understanding of the requirements of circular MCPs in a project facilitates extensive upfront planning and designing for circularity and offsite construction. For instance, the client or owner must understand that construction materials need to be circular and recyclable to ensure reuse after the design economic life of the building (Kyrö et al., 2019). The client must also understand the tight demand for funding in circular MCPs and the transport restrictions defining the dimensions of the module envelope (Li, 2020). The early understanding and commitment of the client would ensure that the project is designed for circular and modular construction and adequate funding made available to procure circular construction materials and structural systems (Wuni and Shen, 2020b). It would also facilitate the early collaboration of clients, contractors, production engineers, design managers, and demolition managers to share relevant information required at various lifecycle phases to be incorporated into the design (van den Berg, 2019).

Effective leadership and support of a specialist contractor obtained a mean score of 4.20 and ranked the third most significant CSF for managing circular MCPs in Hong Kong. Choi et al. (2016) found that well-informed leadership of a specialist contractor is required in successfully managing MCPs. The need to integrate CE principles in the design, construction, and supply chain management in circular MCPs reinvents the required contractors' skills and technical expertise (Norouzi et al., 2021). The specialist contractor must know how the choice of construction materials, processes, decisions, and the various stages of the construction process contributes to materials depletion and environmental impact (Kyrö et al., 2019). Such contractors must understand how to integrate CE principles into the design, offsite factory production, transportation, and onsite assembly of modules in MCPs (Wuni and Shen, 2020b). It is also crucial for the specialist contractors to have technical expertise in design for manufacture and assembly, design for CE, tolerance management, connection systems, production engineering, and value engineering (Fraser et al., 2015).

Obtaining a mean score of 4.19, adequate knowledge and experience of the project team were ranked the fourth most significant CSF for managing circular MCPs in Hong Kong. Blismas (2007) and Choi et al. (2016) found adequate relevant knowledge of project participants as a significant CSF for implementing MCPs. Several players are involved in the co-creation of circular MCPs. These project participants are situated at various stages of the delivery chain and provide interdependent roles and services in circular MCPs. Notably, design managers and demolition managers should have adequate knowledge of circular construction materials and the information required at various stages of the project lifecycle to ensure that CE principles are integrated into the design to facilitate reuse and recycling of building components and materials at the economic life of the projects (van den Berg, 2019). Production engineers (manufacturers) must understand CE and lean production principles to make valuable contributions in the design and ensure cleaner production of the modules to support the goals of circularity and modular construction in the project.

Collaborative working and information sharing among project teams received a mean score of 4.17 and ranked the fifth most significant CSF for managing circular MCPs in Hong Kong. Collaboration, communication, and information sharing constitute the most documented CSF for various innovative construction projects (Wuni and Shen, 2020b). Collaborative working and information sharing enable various project team members situated at different supply chain stages to be abreast of key decisions and processes throughout the delivery of circular MCPs (Norouzi et al., 2021). The collaborative effort enables parties from all tiers of the supply chain to share a common goal of achieving circularity in MCPs. It prevents dysfunctional conflicts, facilitates a more streamlined project delivery process, and encourages proactive problem-solving through knowledge sharing between downstream and upstream project participants. For instance, van den Berg (2019) considered the design and demolition stages as components of a continuous cycle of material banks in circular building projects where key decisions, activities, and information usage significantly influence material reduction, reuse, and recycling. Hence, information at demolition and design stages of circular MCPs can effectively manage the activities significantly impacting material consumptions and wastage (ibid). As such, collaborative work and information sharing throughout the lifecycle are essential to ensure that design managers can leverage relevant information from previous and later demolition stages to inform key decisions and specifications of materials, geometry, and configurations of circular MCPs. It would also enable demolition managers to use information from previous and later design stages. Norouzi et al. (2021) corroborated that collaboration and information sharing among project participants are required to ensure that activities at various levels of the supply chain significantly reduce the environmental impact and material wastage in circular MCPs.

4.2 Principal success factors for managing circular modular construction projects in Hong Kong

The EFA grouped the significant CSFs into three principal success factors (PSFs) for managing circular MCPs in Hong Kong, including PSF1 (effective supply chain management), PSF2 (competence and early commitment), and PSF3 (collaboration and information management). Table 5 summarizes the factor loading and eigenvalues of the PSFs for circular MCPs.

Table 5. Factor loadings and eigenvalues of the principal success factors for circular modular construction projects

ID	Critical success factors/Principal success factors	Factor loadings		
		1	2	3
PSF1	**Effective supply chain management**			
CSF22	Use of hedging strategies and transport delay avoidance	0.714	-	-
CSF10	Integrating circular economy principles into the supply chain of modular construction projects	0.631	-	-
CSF8	Extensive upfront planning for circular modular construction projects	0.629	-	-
CSF17	Effective management of critical tolerances between interfaces	0.603	-	-
CSF7	Design for manufacture, assembly, and circular economy	0.586	-	-
CSF23	Adequate lead time for the bespoke processes of circular modular construction projects	0.574	-	-
CSF14	Effective coordination of onsite and offsite work packages	0.526	-	-
CSF20	Use of just-in-time delivery arrangement	0.469	-	-
PSF2	**Competence and early commitment**		-	-
CSF18	Early engagement of certification body for factory inspection	-	0.811	-
CSF3	Effective leadership and support of a specialist contractor	-	0.768	-
CSF1	Adequate knowledge and experience of the project team	-	0.762	-
CSF6	Suitable site characteristics and layout	-	0.697	-
CSF2	Early understanding and commitment of the client	-	0.684	-
CSF11	Early and active involvement of critical project stakeholders	-	0.647	-

CSF15	Using suitable structural system and construction material	-	0.538	-
CSF5	Early design completion and freezing	-	0.521	-
PSF3	**Collaboration and information management**	-	-	
CSF4	Collaborative working and information sharing among project teams	-	-	0.761
CSF13	Leveraging information from demolition and design lifecycle stages	-	-	0.715
CSF16	Effective use of building information modelling	-	-	0.657
CSF12	Effective coordination and integration of stakeholders	-	-	0.530
CSF9	Use of collaborative procurement system and contracting	-	-	0.512
Eigenvalue		**8.189**	**3.163**	**2.784**
Variance explained (%)		**35.603**	**13.753**	**12.105**
Cumulative variance explained		**35.603**	**49.356**	**61.461**

PSF1 with an eigenvalue of 8.189 explained 35.603% of the variance in the CSFs. It includes ten CSFs linked to seamless integration and coordination of the supply chain segments of circular MCPs. The most significant CSFs within PSF1 is design for manufacture, assembly, and circular economy (CSF7) with a mean score of 4.08, highlighting the significance of the design stage to circular MCPs (Gibb and Isack, 2003). It involves specifying materials, processes, geometry, configurations, and structural systems during the design stage to ensure that the detailed working drawings facilitate the production and assembly of modules that generate minimal environmental impact, reduce material wastage, and accounts for the reuse and recycling of materials and building components after the economic life of the project (Kyrö et al., 2019).

Closely linked to CSF7 within PSF1 is Extensive upfront planning for circular modular construction projects (CSF8) with the next highest mean score of 3.97. According to Zwikael and Globerson (2006), the planning stage can leverage multidisciplinary efforts and the expertise of diverse project participants to generate relevant design information to optimize manufacturing efficiency and deliver circularity benefits. Extensive planning is crucial because the various stages of the delivery chain and associated construction processes make distinct contributions to the total environmental impact of the project (Norouzi et al., 2021). Thus, a successful circular MCP starts with extensive planning at the outset to integrate CE principles into the supply chain of MCPs (CSF10).

Further, Gibb and Isack (2003) discussed the need to provide an adequate lead time for the bespoke processes of circular modular construction projects (CSF23). It is essential to provide enough design and factory production lead times to explicitly consider and integrate circularity and modular construction requirements in the project (Zhai et al., 2017). During the construction process, it is essential to effectively coordinate onsite and offsite work packages (CSF14) to ensure smooth project continuity and avoid expensive and systemic disruptions in the delivery chain. Massive materials can be wasted during factory production and onsite assembly of the modules. Hence, effective use of document management system (CSF21) and inventory management and control (CSF19) of resources, including materials and equipment, are essential to achieve the objectives of circular MCPs (Blismas, 2007). Also, leveraging just-in-time delivery arrangement (CSF20) and hedging strategies (CSF22) are considered relevant practices to minimize onsite shortages of modules and associated impacts on costs and schedules of circular MCPs (Zhai et al., 2018).

PSF2 with an eigenvalue of 3.163 explained 13.753% of the variance in the CSFs. It comprises eight CSFs linked to the competence of the project team, suitable project characteristics, and early commitment to both CE and modular construction in the project. The top four most significant CSFs within PSF2 include early design completion and freezing (CSF5), early understanding and commitment of the client (CSF2), effective leadership and support of a specialist contractor (CSF3), and adequate knowledge and experience of the project team (CSF1). These CSFs have been discussed in section 4.1. The next most crucial CSF is the early and active involvement of critical project stakeholders (CSF11). It is essential to actively and frequently involve the client or owner and key project team members such as designers, manufacturers, contractors, project managers, and logistics companies to leverage their relevant inputs to ensure that various decisions and processes significantly improve the circularity of MCPs. Another important CSF is the specification, selection, and use of a circular structural system and construction materials (CSF15) that have a minimal environmental impact and lend themselves to reuse and recycle after the economic life of the circular MCP. Due to the nature of lands in Hong Kong, a site with flat and simple terrain, adequate width of the local transport network, and minimal surrounding traffic are considered most suitable to enable a smooth transportation and safe delivery of the modules to the site (Development Bureau, 2020; Li, 2020).

PSF3 with an eigenvalue of 2.784 explained 12.105% of the variance in the CSFs. It encompasses five CSFs linked to stakeholder collaboration, communication, and lifecycle information management during the project delivery. The most significant CSF within PSF3 is collaborative working and information sharing among project teams (CSF4), discussed in section 4.1. The next most significant CSF is leveraging information from demolition and design lifecycle stages (CSF13). van den Berg (2019) found that using information from the design and demolition stages to inform critical design decisions reduces material consumption and wastage in circular building projects. The design constitutes the stage where decisions about material use, reuse, and recycling matter most. Hence, incorporating CE principles in the design constitutes an essential step to achieving the comprehensive objectives of circular MCPs. Strategies for leveraging relevant information to improve the circularity of MCPs include collaboration and information sharing among project participants. Depending on the scale of the project, the effective use of building information modelling (CSF16) can improve collaborative working and information sharing throughout the delivery chain of circular MCPs (Wuni and Shen, 2020b). However, few procurement modes and delivery methods encourage the relevant team members to collaborate throughout the project, especially the design stage (Wuni et al., 2021). Thus, using a collaborative procurement system and contracting constitutes a strategic path to achieve the required collaboration throughout the supply chain to achieve the full benefits of circular MCPs (Norouzi et al., 2021).

4.3 Significance indices of the principal success factors for managing circular modular construction projects

The FSE analysis was used to compute the significance indices of the PSFs for managing circular MCPs. Table 6 summarizes the weightings of the CSFs and PSFs for managing circular MCPs in Hong Kong computed using Eqn. (4). PSF1 obtained the highest weighting, followed by PSF2 and PSF3 obtained the least weight. The weightings were not used to rank the PSFs because they are sensitive to the number of CSFs and could be biased towards PSFs containing the highest number of CSFs. Table 7 also summarizes the MFs of the CSFs and PSFs for managing circular MCPs in Hong Kong computed using Eqns. (6), (7), and (8). The MFs of the PSFs were used to compute the significance indices of the PSFs using Eqn. (9) as follows.

Table 6. Weightings of the critical success factors and principal success factors for managing circular modular construction projects

ID	Critical success factors/Principal success factors	Mean	Weightings
PSF1	**Effective supply chain management**	**37.52**	**0.421**
CSF19	Inventory management and control	3.44	0.092
CSF22	Use of hedging strategies and transport delay avoidance	3.51	0.094
CSF10	Integrating circular economy principles into the supply chain of modular construction projects	3.76	0.100
CSF8	Extensive upfront planning for circular modular construction projects	3.97	0.106
CSF21	Effective use of document management system	3.38	0.090
CSF17	Effective management of critical tolerances between interfaces	3.91	0.104
CSF7	Design for manufacture, assembly, and circular economy	4.08	0.109
CSF23	Adequate lead time for the bespoke processes of circular modular construction projects	3.82	0.102
CSF14	Effective coordination of onsite and offsite work packages	3.84	0.102
CSF20	Use of just-in-time delivery arrangement	3.81	0.102

PSF2	**Competence and early commitment**	**32.38**	**0.364**
CSF18	Early engagement of certification body for factory inspection	3.64	0.112
CSF3	Effective leadership and support of a specialist contractor	4.20	0.130
CSF1	Adequate knowledge and experience of the project team	4.19	0.129
CSF6	Suitable site characteristics and layout	3.79	0.117
CSF2	Early understanding and commitment of the client	4.23	0.131
CSF11	Early and active involvement of critical project stakeholders	4.05	0.125
CSF15	Using suitable structural system and construction material	3.97	0.123
CSF5	Early design completion and freezing	4.31	0.133
PSF3	**Collaboration and information management**	**19.170**	**0.215**
CSF4	Collaborative working and information sharing among project teams	4.170	0.218
CSF13	Leveraging information from demolition and design life-cycle stages	3.970	0.207
CSF16	Effective use of building information modeling	3.550	0.185
CSF12	Effective coordination and integration of stakeholders	3.840	0.200
CSF9	Use of collaborative procurement system and contracting	3.640	0.190

$S_{PSF1} = (0.00, 0.05, 0.30, 0.45, 0.19) * (1, 2, 3, 4, 5)$

$= (0.00*1) + (0.05*2) + (0.30*3) + (0.45*4) + (0.19*5)$

= **3.765 (Significant)**

$S_{PSF2} = (0.01, 0.03, 0.19, 0.45, 0.33) * (1, 2, 3, 4, 5)$

$= (0.01*1) + (0.03*2) + (0.19*3) + (0.45*4) + (0.33*5)$

= **4.060 (Significant)**

$S_{PSF3} = (0.01, 0.05, 0.24, 0.47, 0.24) * (1, 2, 3, 4, 5)$

$= (0.01*1) + (0.05*2) + (0.24*3) + (0.47*4) + (0.24*5)$

= **3.875 (Significant)**

Table 7. Membership functions of the critical success factors and principal success factors for managing circular modular construction projects

ID	Principal/Critical success factors	W_i	MFs (Level 2)	MFs (Level 1)
PSF1	**Effective supply chain management**			**(0.00, 0.05, 0.30, 0.45, 0.19)**
CSF19	Inventory management and control	0.092	(0.00, 0.08, 0.50,0.32, 0.09)	
CSF22	Use of hedging strategies and transport delay avoidance	0.094	(0.01, 0.09, 0.38, 0.44, 0.09)	

CSF10	Integrating circular economy principles into the supply chain of modular construction projects	0.100	(0.02, 0.05, 0.26, 0.49, 0.18)	
CSF8	Extensive upfront planning for circular modular construction projects	0.106	(0.01, 0.03, 0.21, 0.51, 0.25)	
CSF21	Effective use of document management system	0.090	(0.00, 0.13, 0.44, 0.36, 0.08)	
CSF17	Effective management of critical tolerances between interfaces	0.104	(0.00, 0.03, 0.26, 0.50, 0.22)	
CSF7	Design for manufacture, assembly, and circular economy	0.109	(0.00, 0.03, 0.21, 0.39, 0.36)	
CSF23	Adequate lead time for the bespoke processes of circular modular construction projects	0.102	(0.00, 0.04, 0.25, 0.56, 0.15)	
CSF14	Effective coordination of onsite and offsite work packages	0.102	(0.01, 0.03, 0.29, 0.47, 0.21)	
CSF20	Use of just-in-time delivery arrangement	0.102	(0.00, 0.06, 0.30, 0.41, 0.23)	
PSF2	**Competence and early commitment**			**(0.01, 0.03, 0.19, 0.45, 0.33)**
CSF18	Early engagement of certification body for factory inspection	0.112	(0.01, 0.08, 0.37, 0.36, 0.19)	
CSF3	Effective leadership and support of a specialist contractor	0.130	(0.01, 0.02, 0.12, 0.48, 0.38)	
CSF1	Adequate knowledge and experience of the project team	0.129	(0.01, 0.01, 0.15, 0.46, 0.38)	
CSF6	Suitable site characteristics and layout	0.117	(0.00, 0.04, 0.30, 0.48, 0.18)	
CSF2	Early understanding and commitment of the client	0.131	(0.00, 0.03, 0.09, 0.48, 0.39)	
CSF11	Early and active involvement of critical project stakeholders	0.125	(0.01, 0.04, 0.15, 0.50, 0.31)	
CSF15	Using suitable structural system and construction material	0.123	(0.00, 0.04, 0.23, 0.44, 0.29)	
CSF5	Early design completion and freezing	0.133	(0.01, 0.01, 0.12, 0.39, 0.47)	
PSF3	**Collaboration and information management**			**(0.01, 0.05, 0.24, 0.47, 0.24)**
CSF4	Collaborative working and information sharing among project teams	0.218	(0.01, 0.01, 0.12, 0.53, 0.33)	
CSF13	Leveraging information from demolition and design lifecycle stages	0.207	(0.01, 0.03, 0.22, 0.48, 0.26)	
CSF16	Effective use of building information modelling	0.185	(0.01, 0.13, 0.33, 0.37, 0.16)	
CSF12	Effective coordination and integration of stakeholders	0.200	(0.01, 0.03, 0.15, 0.60, 0.21)	
CSF9	Use of collaborative procurement system and contracting	0.190	(0.00, 0.08, 0.39, 0.34, 0.19)	

The significance indices of the PSFs are within the second level of the FSE index system established in step 1. The weightings of the PSFs (see Table 6) include PSF1 (0.421), PSF2 (0.364), and PSF3 (0.215). The MFs of the PSFs (see Table 7) include PSF1 (0.00, 0.05, 0.30, 0.45, 0.19), PSF2 (0.01, 0.03, 0.19, 0.45, 0.33), and PSF3 (0.01, 0.05, 0.24, 0.47, 0.24). Given the weightings/MFs of the PSFs and grade alternatives of the rating scale, the overall significance index of the 23 CSFs for managing circular MCPs in Hong Kong was computed using Eqns. (7), (8), and (9) as follows:

$W_{Overall} = (0.421, 0.364, 0.215)$

$$R_{Overall} = \begin{bmatrix} MF_{PSF1} \\ MF_{PSF2} \\ MF_{PSF3} \end{bmatrix} = \begin{bmatrix} 0.00 & 0.05 & 0.30 & 0.45 & 0.19 \\ 0.01 & 0.03 & 0.19 & 0.45 & 0.33 \\ 0.01 & 0.05 & 0.24 & 0.47 & 0.24 \end{bmatrix}$$

$$D_{Overall} = W_{Overall} \bullet R_{Overall} = (0.421, 0.364, 0.215) \bullet \begin{bmatrix} 0.00 & 0.05 & 0.30 & 0.45 & 0.19 \\ 0.01 & 0.03 & 0.19 & 0.45 & 0.33 \\ 0.01 & 0.05 & 0.24 & 0.47 & 0.24 \end{bmatrix}$$

$D_{Overall} = (0.005, 0.046, 0.247, 0.452, 0.250)$

$S_{Overall} = (0.005, 0.046, 0.247, 0.452, 0.250) * (1, 2, 3, 4, 5)$

$= (0.005*1) + (0.046*2) + (0.247*3) + (0.452*4) + (0.250*5)$

= **3.896 (Significant)**

The FSE analysis revealed that the 23 CSFs collectively have a significant impact on the success of circular MCPs in Hong Kong. The overall significance index of 3.896 shows that each of the CSFs constitutes a relevant practice or process for managing circular MCPs. Also, the FSE analysis indicated that the three PSFs for managing circular MCPs in Hong Kong are significant and require the full attention of project managers. The most crucial PSF for managing circular MCPs in Hong Kong is relevant competence and early commitment, which obtained the highest significance index of 4.060 on a 5-point rating scale. The next important PSF is collaboration and information management (3.875), followed by effective supply chain management (3.765). These findings are exciting and representative because circular MCPs require bespoke competencies of project participants, early commitment, effective collaboration, information management, stakeholder management, and seamless supply chain integration (Kyrö et al., 2019; Norouzi et al., 2021; Wuni and Shen, 2020b).

Given the expanding circularity gap in the construction industry, construction organizations have a vested interest in circular MCPs. Thus, the findings have significant practical implications for project stakeholders to achieve the full benefits of CE and modular construction in construction projects. First, the study developed a set of specific CSFs for implementing circular MCPs, which, until now, have not received attention, yet may serve to improve the success of circular MCPs. The study also discussed the stages of the circular MCPs where the various CSFs are most influential and the benefits they can provide. Second, previous studies have primarily focused on the conditions that predicate the success of either CE or modular construction adoption, often suggesting policy-related favorable conditions (Wuni and Shen, 2020b). However, this study revealed that successfully implementing and managing circular MCPs require critical attention to relevant processes, decisions, and conditions in planning, design, factory production, and onsite assembly stages. Notably, the findings exposed the importance of extensive planning and the design stage to a successful circular MCP, highlighting the need for front-end collaborative planning, proactive design solutions, and incorporating downstream (e.g., demolition requirements) information into the design of circular MCPs. Third, the study delineated competencies of project participants, early commitment, collaboration, information management, and supply chain management as the principal management areas in which results, if they are satisfactory, will ensure successful implementation of circular MCPs. Thus, the findings provide project managers with knowledge of critical areas worth considering when implementing circular MCPs.

The study's findings also have significant theoretical implications. First, the 23 CSFs identified in the study constitute the first theoretical set of conditions that predicate success in circular MCPs. It contributes to the theory of CSFs in construction, especially those of CE and modular construction. The identified CSFs may form the basis for future studies addressing the successful implementation of circular MCPs. Second, the framework of PSFs, including effective supply chain management, competence and early commitment, and collaboration and information management, provide a broader theoretical perspective of how best to manage circular MCPs. They can be used to develop a triadic conceptual model or framework of the CSFs for managing circular MCPs.

5. Guidelines for integrating circular economy principles into modular construction projects

A concept well-known but not used in the real world is, in effect, useless. Integrating CE principles into MCPs offers excellent opportunities but a challenging path to improve resource efficiency and minimize the irreversible environmental impact of construction projects. Construction practitioners, clients, and stakeholders have encountered tremendous challenges in converting the CE from neat theory into replicable practice. As a recipe for success, a great degree of flexibility and reflection is crucial in the early integration of CE principles in MCPs. The following provides the much-needed stage-based practical and technical guidance on how project teams, clients, and practitioners can transition smoothly towards integrating CE principles into MCPs.

5.1 Organizational level

- Construction organizations should upskill and provide relevant professionals with the required competencies and expertise to implement circular construction projects.
- Construction organizations should modify their business models across the entire value chain to incorporate alternative processes to create, deliver, and capture value in MCPs without wasting materials and depleting resources.
- Construction companies should understand the opportunities associated with CE, including de-risking project pipelines, generating reliable lower-risk cash flow, and creating long-standing relationships with clients.

5.2 Project strategic definition stage

- The client and project team should consider CE as a business strategy rather than just a sustainable requirement. Hence, the business case for implementing CE principles in MCPs must demonstrate how optimum value can be derived from the material and products throughout the lifecycle
- The client and project team should establish an overarching and clear objective from the outset to integrate circular business models in collaboration with the whole value chain. Thus, the strategic brief of the client should declare a clear vision to apply CE principles in the MCP.

5.3 Inception and planning stage

- The project team should use a whole building lifecycle approach and circular thinking to inform extensive front-end planning for integrating CE principles into the MCP.
- The project brief should set clear objectives for integrating CE principles (e.g., specify zero waste) in the MCP.

- The project should adopt an integrated delivery method that facilitates collaboration and information sharing among all players (e.g., contractors, manufacturers, suppliers) with vested financial interests shared across the whole value chain.
- There should be early understanding and commitment to the common CE mission and sustainable goal in the project.
- A competent demolition contractor should be engaged to provide a pre-demolition and pre-refurbishment audit of the project site early upfront.
- The planning team, including carbon, waste, and cost consultant, should identify the information and data required to implement CE principles throughout the project.

5.4 Design stage

- The client should organize a workshop bringing together the contractor, designers, suppliers, and facility managers to explore CE solutions in the MCP.
- The client must allocate adequate lead time for the bespoke processes of integrating CE principles in MCPs.
- The design approach to integrating CE principles into MCPs must adopt a systems-thinking philosophy considering sustainability frameworks in which construction businesses operate.
- The design team, facility manager, and contractor should collaborate, commit, develop, and agree on CE design objectives with specific metrics and targets for the MCP.
- Designers, manufacturers, suppliers, and urban miners should collaborate to identify and incorporate reused elements into the design.
- The design team should explicitly design out waste, pollution, and excessive material usage at the outset of the MCP.

- The design team should explicitly design the MCP for standardization, modularization, longevity, resource efficiency, disassembly, deconstruction, adaptability, flexibility, recoverability, and reduced embodied carbon over the whole building lifecycle.
- Explicitly design the MCP to use reclaimed materials, remanufactured components, low-impact new materials, and recycled content or secondary materials.
- Consider designing the MCPs in layers to ensure that the finishes allow access to services, accessibility, and replaceability of services, non-structural partitions, and avoiding interdependency of structural frame and façade.
- The design team and client should consider realistic alternative lifetimes for the MCP. The design must consider possible external factors (e.g., shifting planning policy, changes in occupant needs) that could shorten the economic life of the building.
- Known end users and the client must be explicitly engaged in decisions and use analysis informing the overall design philosophy and approach for the building and each element.

5.5 Material procurement

- The client should ensure early of the contractor and partnering within the supply chain to promote transparency and visibility throughout the supply chain.
- The client, suppliers, and contractors should ensure responsible sourcing of materials, encompassing the elimination of hazardous substances and increasing recycled content.
- The procurement tender should specify reverse logistics that considers a delivery and return logistics option to recover materials
- Where possible, the contractor and suppliers should arrange 'product as service" systems rather than outright purchase

5.6 Factory production of modules

- The client should monitor the CE metrics with contractor and supply chain stakeholders
- The production engineers should investigate alternative resource-efficient materials and products easy to repair and disassemble.
- Use materials with recycled content and select new materials that can be recycled, reused or composted at the end of their first life.
- Use products with labels such as Cradle to Cradle and Nature Plus and select products designed for disassembly and can be manufactured or reused at the end of their first life.

5.7 Onsite assembly and handing over stage

- The project team should review the outcomes of the MCP against the established CE objectives
- The design team, contractor, and supply chain parties should benchmark the lessons learned for continuous improvement.

6. Conclusions

This paper developed critical success factors for managing circular modular construction projects in Hong Kong. The research process comprised a focused literature review, pilot interviews, and questionnaire survey of registered construction industry practitioners in Hong Kong. The resulting questionnaire data containing 117 valid responses were analyzed using mean scores, exploratory factor analysis, and fuzzy synthetic evaluation.

- The mean score analysis revealed twenty-one (21) significant critical success factors for managing circular modular construction projects in Hong Kong.

- The top five most significant critical success factors include early design completion and freezing, early understanding and commitment of the client, effective leadership and support of a specialist contractor, adequate project team knowledge and experience, and collaborative working and information sharing among project teams.
- The significant critical success factors were grouped into three principal success factors: effective supply chain management, competence and early commitment, and collaboration and information management, explaining about 61.461% of the variance of the critical success factors for managing circular modular construction projects.
- The fuzzy synthetic evaluation analysis demonstrated that the three principal success factors were significant as they scored significance indices greater than 3.50 on the 5-point rating scale.

The findings made significant scientific, theoretical, and practical contributions to the science and practice of circular modular construction and sustainable construction.

- The findings generate an exclusive set of practices and processes for successfully implementing circular modular construction projects. It revealed the importance of the planning and design stages for achieving circularity in modular construction projects.
- The study also described specific processes associated with the significant critical success factors, providing practical knowledge to project stakeholders when implementing circular modular construction projects.
- The study established the first set of critical success factors and a triadic framework of principal success factors for managing circular modular construction projects.

Despite the contributions, the study has some limitations.

- Though due diligence was made to identify the most relevant critical success factors for managing circular modular construction projects, the list may not be exhaustive.

- The relative importance of the critical success factors is sensitive to context; hence, the priority list in the study may be different in other countries or regions. However, the identified critical success factors are linked to the standard processes and requirements of circular modular construction projects and relevant to other contexts.
- The identified critical success factors were ranked based on experts' opinions and not augmented with case studies. Nevertheless, critical success factors are primarily identified through surveys, protecting the legitimacy and reliability of the findings.
- In the future, it would be interesting to develop critical success processes for managing circular modular construction projects because critical success factors are rarely specific enough for project managers to apply.

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