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Unpacking the Dynamics of Synergising Circular Economy (CE) Principles in Modular Buildings

Abstract

Introduction: Systemic building design is a critical starting point for enabling Circular Economy (CE) transitions in the Building Construction Industry (BCI) and advancing modern methods such as Industrialised Construction (IC). However, in practice, design approaches promoting circularity and those supporting manufacturing-led construction are often pursued separately, creating misalignments that limit both sustainability and productivity outcomes. Design for Circular Manufacturing and Assembly (DfCMA) is proposed as an integrative framework aligning Design for Circularity (DfC) with Design for Manufacturing and Assembly (DfMA). Proponents of DfC aim at both contributing to and benefiting from worldwide CE thrusts, while advocates of DfMA separately point to multiple benefits in boosting productivity, quality and reliability in particular. This paper presents a case for synergising these two major thrusts in the BCI, by focusing on their shared and complementary values, factoring in inevitably competing values and operational protocols that could result in complex interactions and inter-dependencies.

Methods: Systems Dynamics Modelling (SDM) was therefore adopted to capture the complexities, model their dynamics and next help identify ways forward following this integrated modelling of the DfCMA constructs identified in the study underling this paper. Accordingly, this study develops a Causal Loop Diagram (CLD) as the conceptual modelling foundation for SDM to reveal the systemic relationships governing DfCMA. The causal structure of these constructs was examined through methodological triangulation, combining qualitative insights from a Delphi study with twelve BCI experts and quantitative validation through a questionnaire survey analysed using Partial Least Squares–Structural Equation Modelling (PLS-SEM).

Results and Discussion: The empirically-supported structural relationships among eighteen DfMA variables, eighteen DfC variables, and six performance variables were mapped through developing the CLD. The resulting CLD captures the dynamism and complexity of integrating CE principles and practices of modular building design owing to the stakeholders that co-create and co-evaluate at varying degrees of connectivity across the construction value chain and the intricacy of the product itself: for example, materials and components in buildings have their own life cycles and functions, while dynamically interacting with each other over space and time, thereby also influencing the state and performance levels of each other, over the lifespan of a building.

Keywords: Causal-Loop Diagram (CLD), Circular Economy (CE), Design for Circularity (DfC), Design for Circular Manufacturing and Assembly (DfCMA), Design for Manufacturing and Assembly (DfMA), Modular Building, Structural Equation Modelling (SEM), Systems Dynamics Modelling (SDM).

1 Introduction

The global use of secondary raw material has steadily declined from 9.1% of total material inputs in 2018 to 8.6% in 2020, to 7.2% in 2023, up to 6.9% in 2025 (Circle Economy, 2025). Despite widespread recognition of the need to transition, the global economy remains only about 6% circular, manifesting incongruities among legislative, administrative facets of Circular Economy (CE) transition (Ghaffar et al., 2020). Among the sectors exerting the greatest pressure on global resources is the Building Construction Industry (BCI), which consumes approximately 40% of the world's natural resources, generates 40% of global waste, accounts for 35% of energy consumption, and contributes 33% of CO_2 emissions (United Nations Environment Programme, 2020; Van Stijn & Gruis, 2020). Meanwhile, the burgeoning BCI, driven by needs, such as the global deficit in housing, that demands faster and better-quality construction methods. For example, a global housing deficit of 1.6 billion units is projected to rise by an additional 3 billion by 2050 (Charef, 2022). Further, urbanisation trends further intensify this demand, with 60% of the world's population expected to reside in urban areas by 2030, and 70% by 2050 (Ferdous et al., 2019), when the global population is anticipated to reach 9.7 billion (Sun et al., 2020). Compounding this challenge is the acute shortage of affordable housing for low and middle-income households in urban centres (Zhai et al., 2014). In this context, Industrialised Construction (IC), particularly modular buildings has emerged as a compelling alternative to traditional site-based construction, with its proven benefits such as improved time efficiency, enhanced quality, better health and safety, reduced life cycle costs and significant waste minimisation (Obi et al., 2023). These benefits, however, require design frameworks tailored to the unique characteristics of IC, embedding manufacturing principles and collaborative practices from the outset. Design for Manufacturing and Assembly (DfMA) is one such framework with strong relevance to IC (Gao et al., 2020). Similarly, CE scholarship emphasises that building design is the critical starting point for circularity, with approximately 80% of environmental impacts determined during the design stage (Campioli et al., 2018). Design for Circularity (DfC), grounded on Porter's value chain theory, provides a systems-thinking approach that supports multi-criteria decision-making across stakeholders to create and retain circular value throughout the building life cycle (Dewagoda, Ng, & Chen, 2022; Dewagoda, Ng, & Kumaraswamy, 2022).

Recognising the complementary strengths of DfC and DfMA, Dewagoda et al. (2024) introduced the concept of 'Design for Circular Manufacturing and Assembly (DfCMA)'. DfCMA is conceptualised as a unified design framework that simultaneously enhances productivity and circularity by enabling modular building to be manufactured efficiently in factory environment, while narrowing, slowing, and closing resource loops based on circular value creation and retention across the whole building life cycle. The envisioned output of DfCMA is the 'circular modular building', a modular building designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles (Dewagoda et al., 2024). Such buildings are expected to deliver value through rationalised design process, improved material selection, optimised planning and logistics and deliberate circularity strategies that retain value across the Whole Life Cycle (WLC). Building further on this concept, Dewagoda, Kumaraswamy, et al. (2025) identified the key constructs underpinning DfCMA and analysed them using Exploratory Factor Analysis (EFA) and Fuzzy Synthetic Evaluation (FSE). Subsequently, Dewagoda, Chen, et al. (2025) confirmed that these DfCMA constructs' significant influence the realisation of circular modular building by synergising DfMA and DfC in IC. Although the key constructs of DfCMA have been identified, the dynamic interplay, inter-dependencies and feedback mechanisms among these constructs remained unexplored. The system of DfCMA constructs operating across the circular value chain of a modular building can be characterised as a 'complex adaptive system' whose behaviour unfolds through spatial and temporal interactions (Richmond, 1993). Understanding such systems requires a systems-thinking approach that identifies interconnections, maps cause-effect feedback loops and reveals the structural drivers of system behaviour (Arnold & Wade, 2015). Therefore, the next logical step was to explore and establish the dynamism of the key constructs of DfCMA that influence WLC of circular modular buildings.

This practical need is particularly urgent. As global circularity continues to decline and construction demand accelerates, the industry faces a dual challenge: delivering buildings faster while dramatically reducing resource consumption and waste. Modular construction offers a pathway to meet this demand, but without a clear understanding of how productivity-oriented design principles (DfMA) interact with circularity-oriented principles (DfC), the sector risks perpetuating linear, resource-intensive practices in a new industrialised form. Establishing the dynamic behaviour of DfCMA constructs is therefore essential for guiding designers, manufacturers, policymakers, and supply chain actors toward decisions that simultaneously enhance efficiency and circularity. Advancing on, this study aims to develop a Causal-Loop Diagram (CLD) based on Systems Dynamics Modelling (SDM) to unveil the dynamics between these key constructs of DfCMA. By developing a CLD, this study provides a foundational systems-level understanding of how circular value can be created, amplified, or eroded throughout the modular building life cycle. This insight is critical for operationalising CE principles in practice and for enabling the construction sector to respond effectively to global environmental and socio-economic pressures. To achieve this, a multi-step methodological triangulation approach was applied to identify and validate the structural relationships, i.e., structural relationships among DfCMA constructs using the methods explained in Section 3. The theoretical underpinning of the conceptual model is presented in Section 3, followed by empirical results derived from a questionnaire survey and a Delphi study in Section 4. Section 5 discusses the findings in relation to extant literature and Section 6 conveys the conclusions along with recommendations for future research.

2 Dynamic Hypotheses of DfCMA: Conceptual Model

According to the European Commission (2015), CE seeks to retain the value of products for as long as possible by extending and/or intensifying their utilisation, closing the loop between post-use and production, and reducing the resource intensity of products. Value creation and retention, therefore, lie at the core of CE, which aims to keep resources at their ‘highest utility and value’ within the economic system (Ellen MacArthur Foundation, 2015). From an organisational perspective, a Circular Business Model (CBM) must create value not only for the firm itself, but also for customers, supply chain partners and society at large (Nußholz et al., 2020). When the CBM is applied across the WLC, treating the building as the unit of analysis, circular value creation occurs during extraction, manufacturing, and assembly, while circular value retention is realised during maintenance and End-of-Life (EoL) processes (Kedir & Hall, 2021). The ‘value logic framework’ proposed by Richardson (2008), grounded in Porter’s (1985) value chain theory, provides a consolidated and widely adopted structure for understanding business models (Bocken et al., 2014). Richardson (2008) identifies three core elements: the value proposition, the value creation and delivery system, and the value capture system. This study adopts the ‘Value Logic Framework’ (Richardson, 2008) to conceptualise CE transition in the BCI as follows:

- **Value proposition:** The superior circular value offered by the building’s CBM relative to conventional linear building products, maintaining comparable standards of price, quality, aesthetics, functionality, and safety, while shifting production and consumption patterns toward circularity (Nußholz et al., 2020; Ollár et al., 2020), that contributes to and benefits from the widely accepted and pursued global CE.
- **Value creation and delivery system:** The organisational strategies, value chain structures, activity systems, and stakeholder networks through which the building’s CBM operationalises CE principles and delivers integrated circular building solutions (Ünal et al., 2019).

- **Value capture system:** The revenue and economic models that enable the CBM to generate profit and recover the additional costs associated with CE transition (Nußholz et al., 2020).

The above framework underpins the basis of CE transition schema in the BCI, where the current linear value chain of the BCI is to be reinterpreted circularly to discern radical shifts in the production and consumption patterns. Hence, the term, Construction Industry Circular Value Chain (CICVC) (Dewagoda, Ng, & Chen, 2022; Dewagoda, Ng, & Kumaraswamy, 2022) was introduced, to expand the linear value of the BCI towards the needed circularity. Integrating CE principles into IC particularly, modular construction adds further complexity to an already dynamic system. Table 1 helps to articulate these concepts together, for conceptual clarity.

Table 1: Terminology Related to DfCMA in the BCI

Term	Abbreviation	Definitions used in this Study	Source
Circular Economy	CE	"[CE is] restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times"	Ellen MacArthur Foundation (2015, p. 1)
Construction Industry Circular Value Chain	CICVC	A set of primary activities (Circular Planning & Designing, Circular Material Sourcing, Circular Construction, Circular Resource Management, and Circular Processes at Perceived EoL) and secondary activities (Stakeholder Integration, Inception (5 A's - Awareness, Attitude, Acceptance, Agreement, Apprehension), Continuous Circular Assessment, Information Management, Circular Business Models, Technology Development, and Circular Logistics) implemented across the WLC of a building or infrastructure to drive CE transition in the BCI	Dewagoda, Ng, and Chen, J. (2022)
Design for Manufacturing and Assembly	DfMA	DfMA is a design approach that specialises in the design for ease of manufacture of the collection of parts that will form the product after assembly (DfM) and the design of the product for ease of assembly (DfA).	Wasim et al. (2022); Royal Institute of British Architects (2021)
Design for Circularity	DfC	DfC is a systems thinking framework based on Porter's generic value chain theory, accommodating multi-criteria decision-making within an ecosystem of stakeholders to create and retain circular value throughout the whole building life cycle to enable CE transition in the construction value chain	Dewagoda, Ng and Kumaraswamy (2022); Dewagoda, Ng and Chen (2022)
Design for Circular Manufacturing and Assembly	DfCMA	A design framework that facilitates both productivity and circularity by proposing ways to design a modular building that enables not only to be	Dewagoda, Kumaraswamy, Chen, Ng and Jayathunga (2025); Dewagoda, Chen,

		designed to be manu-factured 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	Kumaraswamy, and Ng (2025)
Circular modular building		An optimised modular building that is designed, planned, constructed, used, and deconstructed across its WLC in a manner consistent with CE principles	Dewagoda, Kumaraswamy, Chen, Ng and Jayathunga (2025); Dewagoda, Chen, Kumaraswamy, and Ng (2025)

Consequently, the inherent dynamism of DfCMA within the CICVC must be examined through systems thinking to understand the spatial and temporal interactions and interdependencies that shape system behaviour (Richmond, 1993). To this end, the dynamic propositions of DfCMA constructs were conceptualised by identifying structural relationships among its constituent variables. For clarity, the constructs were organised into DfC variables (C1-C18), DfMA variables (M1-M18), and performance variables (P1-P6) and six groups of DfCMA constructs (CM1-CM5 and DfCMA). Table 2 presents the 18 BCI-specific DfMA constructs, previously derived and validated by Dewagoda, Chen, et al. (2025), along with the scales at which they operate and the CICVC stages at which they materialise when applied during the 'Circular Planning and Designing' stage.

Table 2: Constructs of DfC in the BCI

Code	CICVC Stage	Scale	Construct	Source
C1		**M P S**	Design to close resource loops by treating the building, its materials and components as perpetual assets	(Çetin et al., 2021; Çetin & Kirchherr, 2025; Dewagoda, Kumaraswamy, et al., 2025; Hossain et al., 2020; Marsh et al., 2022; Minunno et al., 2018; Rajaratnam et al., 2023; Satola et al., 2020)
C2		**M P S**	Design to narrow resource loops by reducing the resource consumption per module	(Çetin et al., 2021; Dewagoda, Kumaraswamy, et al., 2025; Eissa & El-adaway, 2024; Li et al., 2014; Marsh et al., 2022)
C3		**P S**	Design to slow resource loops by extending the lifespan of the modules and building components	(Çetin et al., 2021; Dewagoda, Kumaraswamy, et al., 2025; Grussing Michael & Liu Liang, 2014; Minunno et al., 2018; Van Stijn & Gruis, 2020)
C4		**P**	Design for flexible spatial layouts	(Durmisevic, 2018; Geldermans, 2016; Mackenbach et al., 2020; Zairul, 2021)
C5		**P**	Design components that can be upgraded or modified	(Durmisevic, 2018; Geldermans, 2016; Hossain et al., 2020; Kyrö et al., 2019; Minunno et al., 2018; Weerasinghe et al., 2025)
C6		**P**	Design reconfigurable and interchangeable spatial layouts	(Eissa & El-adaway, 2024; Madushika & Lu, 2025; Mesa et al., 2019; Pan & Zhang, 2023; Peiris et al., 2024; Satola et al., 2020; Sonego et al., 2018; Wasim et al., 2022)

Code	CICVC Stage	Scale	Construct	Source
C7		**M P**	Use durable building materials and components in the building design	(Dewagoda, Kumaraswamy, et al., 2025; Durmisevic, 2018; Van Stijn & Gruis, 2020)
C8		**P**	Design for built-in serviceability of components and modules	(Chen & Lu, 2018; Hossain et al., 2020; Kamali & Hewage, 2016; Marsh et al., 2022)
C9	♻	**S**	Design for demountable and mobile modules	(Askar et al., 2022; Çetin & Kirchherr, 2025; Hossain et al., 2020; Jayawardana et al., 2023; Kamali & Hewage, 2016; Kedir & Hall, 2021; Lu et al., 2021; Marsh et al., 2022; Minunno et al., 2020; Minunno et al., 2018; Obi et al., 2023; Roxas et al., 2023; Santos et al., 2024; Satola et al., 2020)
C10	♻	**M P S**	Restore and regenerate natural ecosystems by the building design	(Chen & Lu, 2018; Lu et al., 2021; Mackenbach et al., 2020; Marsh et al., 2022; Minunno et al., 2018; Nuñez-Cacho et al., 2018; Obi et al., 2023; Van Stijn & Gruis, 2020; Wuni & Shen, 2022)
C11		**S**	Integrate clean energy systems in the building design	(Durmisevic, 2018; Jaillon & Poon, 2014; Kyrö et al., 2019; Roxas et al., 2023; Satola et al., 2020)
C12		**M**	Use secondary raw materials in the building design	(Amarasinghe et al., 2025; Çetin et al., 2021; Çetin & Kirchherr, 2025; Geldermans, 2016; Hossain et al., 2020; Kedir & Hall, 2021; Marsh et al., 2022; Nuñez-Cacho et al., 2018; Santos et al., 2024)
C13	♻	**S**	Design for multiple lifecycle use of modules	(Dewagoda, Kumaraswamy, et al., 2025; Ferdous et al., 2019; Van Stijn & Gruis, 2020; Weerasinghe et al., 2025)
C14	♻	**M P S**	Design to recover and recapture components and assemblies	(Bianchi & Cordella, 2023; Chen & Lu, 2018; Ding et al., 2023; Tennakoon et al., 2024; Wijewickrama et al., 2021)
C15		**P**	Design for adaptable spatial layouts	(Chen et al., 2022; Ding et al., 2023; Ferdous et al., 2019; Kamali & Hewage, 2016; Langston & Zhang, 2021; Laovisutthichai et al., 2022; Marsh et al., 2022; Minunno et al., 2018; Obi et al., 2023)
C16	♻	**M P S**	Design for systematic deconstruction of the building	(Amarasinghe et al., 2025; Hossain et al., 2020; Kamali & Hewage, 2016; Li et al., 2014; Marsh et al., 2022; Pan & Zhang, 2023; Satola et al., 2020)
C17		**M P S**	Design out waste in building construction	(Dewagoda, Kumaraswamy, et al., 2025; Kyrö et al., 2019; Van Stijn & Gruis, 2020; Yang et al., 2024)
C18		**S**	Design for energy-efficient building operation	(Antwi-Afari, Ng, Chen, et al., 2023; Eissa & El-adaway, 2024; Tennakoon et al., 2024; Wijewickrama et al., 2021; Wuni & Shen, 2022)

Circular Material Sourcing ♻ Circular Processes at Perceived EoL

Code	CICVC Stage	Scale	Construct	Source
🏭 Circular Manufacturing			M Material-scale	
🏗 Circular Assembly			P Product-scale	
🏢 Circular Resource Management			S System-scale	

Source: Adapted from Dewagoda, Chen, et al. (2025)

Similarly, Table 3 presents the 18 BCI-specific DfMA constructs, as derived and validated by Dewagoda, Chen, et al. (2025), together with the scales at which they operate and the CICVC stages at which they materialise when applied during the 'Circular Planning and Designing' stage.

Table 3: Constructs of DfMA in the BCI

Code	CICVC Stage	Scale	Construct	Source
M1	🏗 ♻	**P**	Reversible inter-module connections	(Antwi-Afari, Ng, Chen, et al., 2023; Durmisevic, 2018; Geldermans, 2016; Jaillon & Poon, 2014; Pan & Zhang, 2023; Roxas et al., 2023)
M2	🏗	**S**	Design for efficient module assembly on-site	(Chen & Lu, 2018; Chen et al., 2022; Gao et al., 2020; Kamali & Hewage, 2016; Lu et al., 2021; Royal Institute of British Architects, 2021)
M3	🏭	**P**	Multi-functional building components and assemblies	(Dewagoda, Kumaraswamy, et al., 2025; Gao et al., 2020)
M4	🏭 🏗	**P**	Standardised dimensions and spatial layouts in modules	(Bao et al., 2022; Chen & Lu, 2018; Geldermans, 2016; Hyun et al., 2022; Jung & Yu, 2022; Wasim et al., 2022)
M5	🏭 🏗	**S**	Design for scalable mass production of modules in the factory and assembly on site	(Kamali & Hewage, 2016; Langston & Zhang, 2021; Royal Institute of British Architects, 2021)
M6	🏭	**P**	Design for integrated assemblies of building components	(Gao et al., 2020; Roxas et al., 2023; Royal Institute of British Architects, 2021)
M7	🏭 🏗	**S**	Repeat identical modules in the building	(Chen & Lu, 2018; Jung & Yu, 2022; Kamali & Hewage, 2016)
M8	🚚	**M**	Reduce the material input to the building by the building design	(Bianchi & Cordella, 2023; Dewagoda, Kumaraswamy, et al., 2025; Jung & Yu, 2022; Sharma et al., 2022; Van Stijn & Gruis, 2020)
M9	🏭	**S**	Volumetric module design	(Abdelmageed & Zayed, 2020; Bao et al., 2022; Building and Construction Authority: Singapore, 2017; Hyun et al., 2022; Kyrö et al., 2019; Langston & Zhang, 2021; Lu et al., 2021; Machado & Morioka, 2021; Roxas et al., 2023; Sonego et al., 2018)
M10	🚚	**M**	Use affordable building materials in the building design	(Chen & Lu, 2018; Dewagoda, Kumaraswamy, et al., 2025; Roxas et al., 2023)
M11	🚚 🏗 ♻	**M P**	Use light-weight building materials and components in the building design	(Bao et al., 2022; Kamali & Hewage, 2016; Tan et al., 2020)
M12	🚚 🏭	**M**	Use manufacturing-friendly building materials in the building design	(Dewagoda, Kumaraswamy, et al., 2025; Jung & Yu, 2022; Pasquire & Connolly, 2003)
M13	🏗	**P**	Error-proof design of structural connections (Poka-Yoke)	(Dewagoda, Kumaraswamy, et al., 2025; Roxas et al., 2023; Royal Institute of British Architects, 2021)
M14	🏭 🏗	**P S**	Simplified spatial and structural layouts of modules	(Bao et al., 2022; Building and Construction Authority: Singapore, 2017; Chen & Lu, 2018; Roxas et al., 2023)

Code	CICVC Stage	Scale	Construct	Source
M15	🚜 🏭 🏗	**M P S**	Compliance with existing quality and safety regulations of building design	(Abd Razak et al., 2022; Building and Construction Authority: Singapore, 2017; Dewagoda, Kumaraswamy, et al., 2025; Hyun et al., 2022; Kamali & Hewage, 2016)
M16	🏗 ♻	**S**	Logistically engineered module design	(Building and Construction Authority: Singapore, 2017; Dewagoda, Kumaraswamy, et al., 2025; Hyun et al., 2022; Langston & Zhang, 2021; Tan et al., 2020)
M17	🏭 🏗 🏢 ♻	**M P S**	Design for the safety of construction and building personnel	(Abd Razak et al., 2022; Ferdous et al., 2019; Kamali & Hewage, 2016; Pasquire & Connolly, 2003; Royal Institute of British Architects, 2021)
M18	🏢	**M P S**	User-centred module design	(Antwi-Afari, Ng, Chen, et al., 2023; Çetin & Kirchherr, 2025; Chen & Lu, 2018; Eissa & El-adaway, 2024; Geldermans, 2016; Kyrö et al., 2019; Marsh et al., 2022; Nuñez-Cacho et al., 2018)

🚜 Circular Material Sourcing
🏭 Circular Manufacturing
🏗 Circular Assembly
🏢 Circular Resource Management
♻ Circular Processes at Perceived End-of-Life (EoL)
M Material-scale
P Product-scale
S System-scale

Source: Adapted from Dewagoda, Chen, et al. (2025)

Although methods for measuring circularity remain in an early and evolving stage with limited consensus on definitive indicators, the most commonly used approaches include Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) (Tokazhanov et al., 2022). While these methods offer valuable sustainability insights, they do not adequately capture circularity at the product or component level across the construction value chain. Consequently, there is a pressing need for overarching indicators capable of assessing circularity at multiple scales of a building's WLC, particularly those that account for adaptability and deconstructability. This need is even more pronounced in modular construction, where novel construction methods require substantial refinement of existing circularity assessment frameworks to accurately evaluate the performance of circular modular buildings. In response, this study adopts circular performance variables P1-P5, derived from established circularity assessment frameworks including Arup's *Circular Building Toolkit* (2020), the European Commission's *LEVELS Framework* (2021), and UKGBC (2023). It is important to note, however, that these variables used in this research are not exhaustive; dimensions such as use-phase recovery potential, EoL waste minimisation, and EoL recovery potential fall outside the scope of this research. Performance variable P6 comprises two components: 'productivity' and 'efficiency', both linked to construction time in circular manufacturing and circular assembly. This variable is particularly appropriate for the present study, as it is widely used in sustainability performance assessments of modular construction (Kamali et al., 2022; Pan & Zhang, 2023; Zhang et al., 2022). Accordingly, to build a computer-simulatable model of the dynamic relationships among these constructs, six DfMA and DfC performance variables (P1–P6) were incorporated into the dynamic hypotheses. These performance variables enable definition through numerical parameters and mathematical equations. Table 4 provides detailed descriptions of these performance variables.

Table 4: Performance Variables in Dynamic Hypotheses of DfCMA in the BCI (P1-P6)

Code	Variable	Description	Source
P1	Upfront Dematerialisation	Delivering the same building using a lower percentage of mass: kg/m^2 *Gross Internal Area (GIA)*	(Arup, 2020; European Commission, 2021; UKGBC, 2023)
P2	Upfront Material Recovery Potential	Materials, products, and components/systems that are remanufactured and recycled in their current form: % Tonnes of total mass	(UKGBC, 2023)
P3	Upfront Waste Minimisation	Overall quantity of waste generated by construction: *kg/m^2 GIA*	(European Commission, 2021; Kamali & Hewage, 2017; Kamali et al., 2018)
P4	Use Phase Adaptability Potential	The ability to be changed or modified to make it suitable for a particular purpose: *% Area of total building*	(Arup, 2020; European Commission, 2021; UKGBC, 2023)
P5	EoL Deconstruction Potential	Design to allow ease of disassembly at the end of life: *% Tonnes of total mass*	(Arup, 2020; European Commission, 2021; UKGBC, 2023)
P6	Construction Productivity and Time Efficiency	• Construction Productivity: Labour productivity: *m^2/h Man-hour*; Machinery productivity: *$m^2/\$$ Machinery cost*; Multifactor productivity: *$m^2/\$$ Costs for labour, material, and machinery* • Design and Construction Time Efficiency: Floor cycle: *days*; Speed of construction: *m^2/day*	(Kamali & Hewage, 2016, 2017; Kamali et al., 2018; Kamali et al., 2022; Pan & Zhang, 2023; Zhang et al., 2022)

The six groups of DfCMA constructs (CM1-CM5 and DfCMA) are informed by the latent factor groups identified through EFA in Dewagoda, Chen, et al. (2025). These groupings do not alter the causal dynamics; rather, they provide a logical structure for presentation and serve as auxiliary variables within the System Feedback Framework (SFF). Table 5 summarises these construct groups (CM1-CM5 and DfCMA).

Table 5: Group Variables of Dynamic Hypotheses of DfCMA Constructs in the BCI (CM1-CM5 and DfCMA)

Code	Construct
CM1	**Design for sustainable and resilient building life cycle management**
C4	Design for flexible spatial layouts
C5	Design components that can be upgraded or modified
C6	Design reconfigurable and interchangeable spatial layouts
C7	Use durable building materials and components in the building design
C8	Design for built-in serviceability of components and modules
C15	Design for adaptable spatial layouts
CM2	**Design to facilitate lean building construction**
M1	Reversible inter-module connections
M2	Design for efficient module assembly on-site
M3	Multi-functional building components and assemblies
M4	Standardised dimensions and spatial layouts in modules
M6	Design for integrated assemblies of building components
M7	Repeat identical modules in the building
M9	Volumetric module design
M10	Use affordable building materials in the building design

M12	Use manufacturing-friendly building materials in the building design
M13	Error-proof design of structural connections (Poka-Yoke)
M14	Simplified spatial and structural layouts of modules
CM3	**Design to incorporate human-centric advanced technologies**
M15	Compliance with existing quality and safety regulations of building design
M17	Design for the safety of construction and building personnel
M18	User-centred module design
C10	Restore and regenerate natural ecosystems by the building design
C11	Integrate clean energy systems in the building design
C18	Design for energy efficient building operation
CM4	**Design to enhance the EoL Recovery Potential of the building**
M11	Use light-weight building materials and components in the building design
M16	Logistically engineered module design
C9	Design for demountable and mobile modules
C13	Design for multiple lifecycle use of modules
C16	Design for systematic deconstruction of the building
CM5	**Design for WLC resource sufficiency of the building**
M8	Reduce the material input to the building by the building design
C12	Use secondary raw materials in the building design
C14	Design to recover and recapture components and assemblies
C17	Design out waste in building construction
DfCMA	**Design for Circular Manufacturing and Assembly**
M5	Design for scalable mass production of modules in the factory and assembly on site
C1	Design to close resource loops by treating the building, its materials and components as perpetual assets
C2	Design to narrow resource loops by reducing the resource consumption per module
C3	Design to slow resource loops by extending the lifespan of the modules and building components

Even though the Correlation Heatmap of DfCMA Latent Factor Groups and Spearman's Rank Correlation Coefficients Heatmap of DfCMA Constructs elucidate a useful abstract of the association between the constructs (Dewagoda, Chen, et al., 2025), further research is needed to investigate whether any of the correlations are 'causative'. According to Barrowman (2014), correlation does not imply causation unless one variable directly causes a change in the other variable. Hence, a multi-step methodological triangulation approach was carried out to explore and establish the empirically-supported structural relationships. Onset, dynamic hypotheses between the DfCMA constructs were formulated based on a thorough literature review. These hypotheses demonstrate the structural relationships between the DfC constructs (C1-C18) and DfMA constructs (M1-M18). For the quantification of the dynamics of the relationships between these constructs, six DfMA and DfC performance variables (P1-P6) were introduced. Furthermore, six groups of DfCMA constructs (CM1-CM5 and DfCMA) as inferred based on the latent factor groups identified through EFA in Dewagoda, Chen, et al. (2025) will provide a logical basis of presentation acting as converters of SDM. Based on these foundations, the conceptual model of dynamic hypotheses representing the structural relationships among the variables to be tested using the Delphi method and Partial Least Squares-Structural Equation Modelling (PLS-SEM) was developed and is presented in Table 6.

Table 6: Hypothesised Structural Relationships in the Conceptual Model of DfCMA Constructs

Code	**Hypothesis**
H1	P1 Upfront Dematerialisation has a positive and statistically significant influence on CM5 Design for WLC resource sufficiency of the building

Code	Hypothesis
H2	P2 Upfront Material Recovery Potential has a positive and statistically significant influence on CM5 Design for WLC resource sufficiency of the building
H3	P3 Upfront Waste Minimisation has a positive and statistically significant influence on CM5 Design for WLC resource sufficiency of the building
H4	C10 Restore and regenerate natural ecosystems by the building design has a positive and statistically significant influence on CM3 Design to incorporate human-centric advanced technologies
H5	M15 Compliance with existing quality and safety regulations of building design has a negative and statistically significant influence on P2 Upfront Material Recovery Potential
H6	P6 Construction Productivity and Time Efficiency has a positive and statistically significant influence on CM2 Design to facilitate lean building construction
H7	P5 EoL Deconstruction Potential Design for demountable and mobile modules has a positive and statistically significant influence on CM4 Design to enhance the EoL Recovery Potential of the building
H8	M16 Logistically engineered module design has a positive and statistically significant influence on CM4 Design to enhance the EoL Recovery Potential of the building
H9	P4 Use Phase Adaptability Potential has a positive and statistically significant influence on CM1 Design for sustainable and resilient building life cycle management
H10	C7 Use durable building materials and components in the building design has a positive and statistically significant influence on CM1 Design for sustainable and resilient building life cycle management
H11	C11 Integrate clean energy systems in the building design has a positive and statistically significant influence on C10 Restore and regenerate natural ecosystems by the building design
H12	M9 Volumetric module design has a positive and statistically significant influence on High Design Complexity
H13	High Design Complexity has a negative and statistically significant influence on P6 Construction Productivity and Time Efficiency
H14	High Design Complexity has a negative and statistically significant influence on Low Design Complexity
H15	High Design Complexity has a negative and statistically significant influence on C4 Design for flexible spatial layouts
H16	Low Design Complexity has a positive and statistically significant influential relationship with P6 Construction Productivity and Time Efficiency
H17	Low Design Complexity has a positive and statistically significant influence on C6 Design reconfigurable and interchangeable spatial layouts
H18	M1 Reversible inter-module connections has a positive and statistically significant influence on P6 Construction Productivity and Time Efficiency
H19	M1 Reversible inter-module connections has a positive and statistically significant influence on P5 EoL Deconstruction Potential
H20	M1 Reversible inter-module connections has a positive and statistically significant influence on C13 Design for multiple lifecycle use of modules
H21	M11 Use light-weight building materials and components in the building design has a positive and statistically significant influence on M16 Logistically engineered module design
H22	P5 EoL Deconstruction Potential has a positive and statistically significant influence on C13 Design for multiple lifecycle use of modules
H23	C13 Design for multiple lifecycle use of modules has a positive and statistically significant influence on C7 Use durable building materials and components in the building design
H24	C6 Design reconfigurable and interchangeable spatial layouts has a positive and statistically significant influence on C4 Design for flexible spatial layouts
H25	C5 Design components that can be upgraded or modified has a positive and statistically significant influence on C4 Design for flexible spatial layouts

Code	Hypothesis
H26	C4 Design for flexible spatial layouts has a positive and statistically significant influence on P4 Use Phase Adaptability Potential
H27	CM1 Design for sustainable and resilient building life cycle management has a positive and statistically significant influence on DfCMA
H28	CM2 Design to facilitate lean building construction has a positive and statistically significant influence on DfCMA
H29	CM3 Design to incorporate human-centric advanced technologies has a positive and statistically significant influence on DfCMA
H30	CM4 Design to enhance the EoL Recovery Potential of the building has a positive and statistically significant influence on DfCMA
H31	CM5 Design for WLC resource sufficiency of the building has a positive and statistically significant influence on DfCMA

The following sub-section outlines the methods used to construct the CLD derived from the conceptual model of dynamic hypotheses. This CLD was subsequently next validated through Hierarchical Component Modelling (HCM) using PLS-SEM and two rounds of Delphi study.

3 Materials and Methods

This study adopted a mixed method research design, integrating both quantitative and qualitative approaches as recommended by Fellows and Liu (2021) (Figure 1). Pragmatism underpins this methodological choice, as it positions the research question, not the method, as the primary driver of inquiry, allowing the use of subjective or objective means as appropriate (Tashakkori & Teddlie, 1998). The central research question of this study: 'What are the dynamics between the key constructs of DfCMA?' necessitates such methodological flexibility.

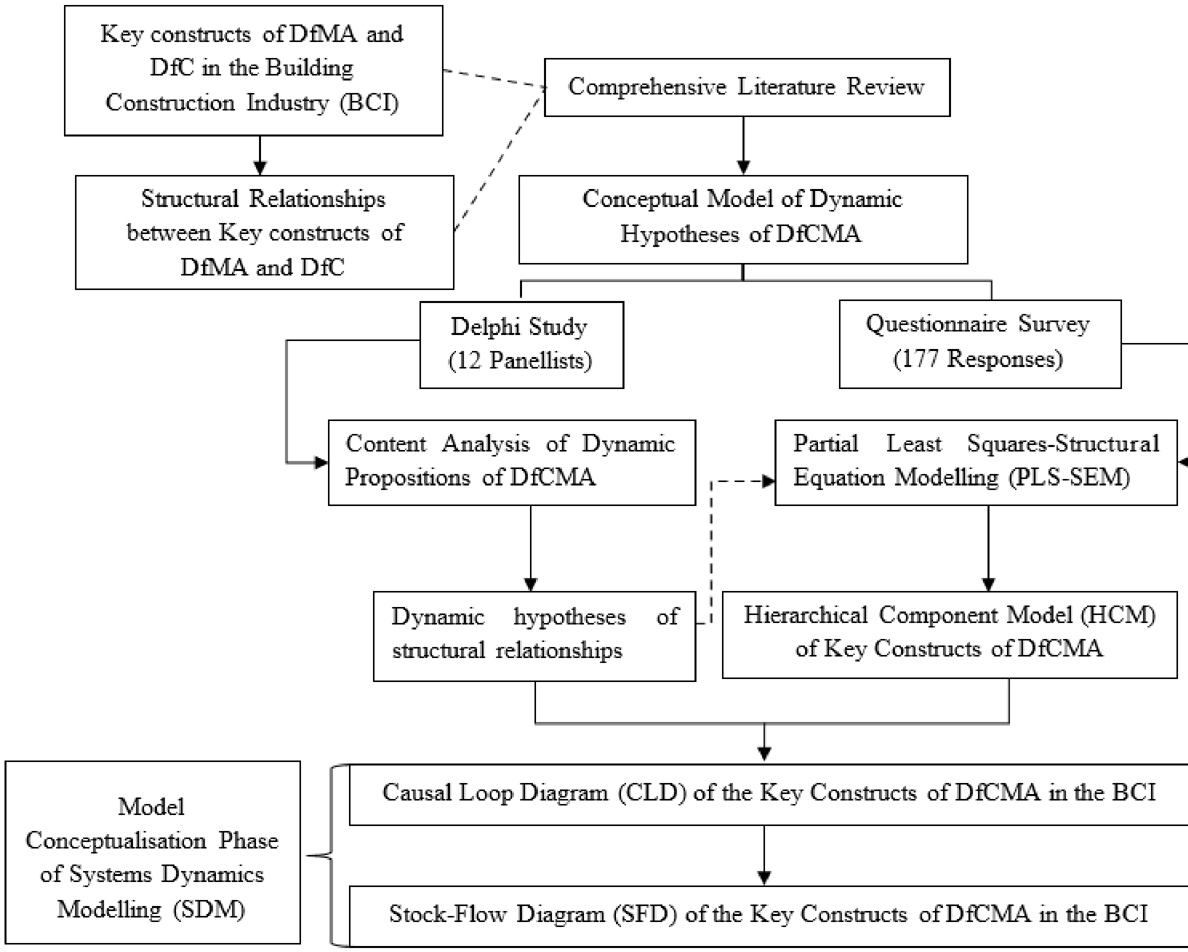


Figure 1: Methodological Framework of the Study

In SDM, the research process begins with the ‘Model Conceptualisation Phase’, which involves defining the model purpose, identifying users, and conceptualising system dynamics (Elsawah et al., 2017). Recognising the foundational importance of this phase (Giordano et al., 2025), this study follows the seminal guidance of Richardson and Pugh (1981) and Sterman (2000), in constructing a CLD that represents the model structure and the dynamic behaviour of the DfCMA constructs. To establish the cause-effect relationships required for the CLD, this study employed *methodological triangulation* by evaluating the empirically-supported structural relationships qualitatively through two rounds of Delphi study, and quantitatively through a questionnaire survey (discussed in detail in the following sub-sections). The use of multiple methods strengthened the robustness of the findings and enhanced the validity of the resulting CLD, which forms the basis for SDM (Bekhet & Zauszniewski, 2012). The DfC variables (C1-C18), DfMA variables (M1-M18), performance variables (P1-P6) and grouped DfCMA constructs (CM1-CM5 and DfCMA) are further discussed in Section 3. The following sub-sections describe the data collection and analysis procedures that informed the development of the CLD of key constructs of DfCMA.

3.1 Qualitative Evaluation of Structural Relationships: Delphi Study

The study conducted a Delphi study to reach expert consensus on the dynamic hypotheses underpinning the CLD. The Delphi method is a structured group communication process designed to facilitate expert judgement on complex problems (Linstone & Turoff, 1975). It is particularly valuable when existing knowledge is limited or fragmented (Beiderbeck et al., 2021), making it well suited to the emerging concept of DfCMA. A Delphi study is characterised by iterative rounds of controlled feedback, participant anonymity, and statistical aggregation of group responses (Landeta, 2006). The selection of an appropriate expert panel is critical to the method's success (Linstone & Turoff, 1975). Although no universal standard exists for panel size, a heterogeneous group of 10-20 experts is generally acceptable for qualitative Delphi studies (Skulmoski et al., 2007). To ensure relevant expertise, panel members were required to meet at least one of the following criteria:

1. Five or more years of academic or industry experience in IC, modular construction, DfMA, Off-Site Construction (OSC), prefabrication or related disciplines and ten or more years of academic or industry experience in the BCI
2. Five or more years of academic or industry experience in circular, sustainable, or green building design/construction or related disciplines, and ten or more years of academic or industry experience in the BCI

Forty-eight qualified professionals and academics, who fulfilled at least one of the above two criteria, were invited, and fifteen agreed to participate in the Round 1. Among them, four (26%) respondents were from Australia, seven (47%) experts were from Asia, three (20%) experts were from Europe, and one (7%) respondents were from Africa. The experts were recruited through referrals, leveraging the professional networks in mainly the Asia-Pacific region combined with snowball sampling to identify the relevant experts using heterogeneous purposive sampling as it allows maximum variation within the sample by deliberately including panellists with varied expertise and viewpoints, often ensuring a range of backgrounds (Saunders et al., 2019). The Delphi experts were contacted via email and *LinkedIn* and interviewed online using *Zoom* or *Microsoft Teams*. In Round 1, participants were presented with eight dynamic hypotheses (Table 5) developed from an extensive literature review comprising DfMA variables, DfC variables, and performance variables (as shown in Tables 1-3) to evaluate how these variables would interact with each other within the building design and how they would influence the WLC of the building. These hypotheses were expressed as 'reality maps', graphical representations of structural relationships intended to support shared understanding and collective reasoning (Linstone & Turoff, 1975; Skulmoski et al., 2007). To enhance contextual insight, experts were asked to assume the role of a multidisciplinary design team tasked with designing a circular modular building. The experts evaluated how the DfMA (M1-M18), DfC (C1-C18), and performance variables (P1-P6) interact within the design process, and influence the building's WLC. For specificity, experts considered a high-rise residential project using Prefabricated Prefinished Volumetric Construction (PPVC), focusing on a corner apartment modules' envelope, including connections, load-bearing walls, roof slab and floor slab. Modules could be reinforced concrete or steel, and the building was assumed to be delivered under a 'Building-as-a-Service' (BaaS) model with the same organisation responsible from Beginning-of-Life (BoL) and EoL. Causation was tested qualitatively using empirical evidence and deductive reasoning, accounting for multi-causality (Boddy, 2019). Two criteria guided this evaluation:

1. The cause precedes the effect, i.e., temporal precedence, and
2. No external variable should distort the observed relationship, i.e., absence of compounding variables (Boddy, 2019).

Round 1 resulted in substantial refinements to the hypotheses, distinguishing confirmed relationships from speculative ones requiring further investigation. Speculative links were removed, and a revised set of hypotheses was prepared for Round 2. Out of the fifteen Round 1 panellists, twelve completed the Round 2 online survey administered via *Qualtrics* platform. Group consensus was reached in the second round of the Delphi study, with minor recommendations that did not alter the logic of dynamic hypotheses, but enhanced the clarity and practicality. Diamond et al. (2014) argue that an agreement percentage exceeding 75% is deemed statistically significant as the cut-off point of achieving consensus, hence was set as the threshold in this research as well. Accordingly, the Delphi process was terminated with the achievement of consensus based on this priori definition of consensus. For links with conflicting polarity assignments, the disagreement was flagged and discussed in Round 2. Causal directionality was determined by retaining unidirectional or dominant-direction links. In cases where bidirectional influence was plausible but asymmetric, stronger direction as judged by the expert panel, was retained. Consensus was achieved in Round 2, with only minor logic-based adjustments that improved clarity without altering the overall causal structure. This concluded the Delphi process. Table 7 summarises the profiles of the Delphi experts, who participated in both rounds.

Table 7: Profile of Panel of Delphi Study Experts

Interviewee Code	Location	Designation	Expertise	Related Areas of Experience	Experience (Years)
DS.1	South Africa	University Lecturer	Quantity Surveying, Construction Management	Sustainable Construction, Construction Procurement	10-20
DS.2	Australia	University Lecturer	Architecture	Circular Construction, Digital Architecture	More than 20
DS.3	Australia	University Lecturer	Construction Management	Construction and Demolition Waste Management, Recycled Materials, Circular Building Design	10-20
DS.4	Sri Lanka	University Lecturer	Quantity Surveying, Construction Management	LC, Green Buildings, Construction Procurement	10-20
DS.5	Australia	University Lecturer	Quantity Surveying, Construction Management	Sustainable Construction, Green Buildings, Construction Information Management	10-20
DS.6	Sri Lanka	University Lecturer	Quantity Surveying, Construction Management	Disaster Management, Sustainable Construction	More than 20
DS.7	Macau (S.A.R.)	University Lecturer	Civil Engineering	Zero-Carbon Buildings, Modular Construction, Construction Robotics	10-20
DS.8	Australia	University Lecturer	Civil Engineering	Sustainable Construction, Smart Construction, Green Building Materials	10-20
BS.9	United Kingdom	University Lecturer	Civil Engineering	Sustainable Construction, Renewable Energy Management	10-20
DS.10	United Kingdom	Environmental Engineer and Researcher	Environmental Engineering, Construction Management	Circular Construction, Sustainable Construction, SDM	10-20
DS.11	Pakistan	University Lecturer	Civil Engineering	Modular Construction, Circular Construction, SDM	More than 20
DS.12	Sri Lanka	General Manager of Sustainable Business	Environmental Management, Construction Management	Sustainable Construction, Construction Safety	10-20

The diversity and depth of their professional backgrounds, spanning modular construction, circular design, industrialised construction, and broader BCI experience serve to validate the credibility of the panel and reinforce the robustness of the findings. By demonstrating that the experts possess the requisite domain knowledge and practical insight, Table 6 substantiates the reliability of the consensus reached and strengthens the methodological rigour of the Delphi process. While the recruitment of panellists from a wide range of disciplines with diversified experience across the topics under investigation, in addition to their geographic spread along with strict maintenance of anonymity in both rounds of the Delphi survey, further minimised the effect of consensus bias. All the panellists had more than 10 years of relevant experience ensuring their in-depth understanding of the BCI while also remaining at the forefront of relevant cutting-edge developments. The anonymity of the expert panellists reduced risks of potential dominance bias in Delphi studies, while controlled feedback at the end of the first round included reasons where necessary, in order to minimise any potential impacts of the bandwagon effect (Hallowell & Gambatese, 2010).

Having established the relationships between the DfCMA constructs qualitatively through two rounds of Delphi study, the next step involved exploring the relationships quantitatively using PLS-SEM based on a questionnaire survey.

3.2 Quantitative Evaluation of Structural Relationships: Hierarchical Component Modelling (HCM) using PLS-SEM

A close-ended questionnaire survey was administered using a five-point Likert scale where 1=Very insignificant, 2=Insignificant, 3=Moderately significant, 4=Significant, and 5=Very significant. The targeted respondents were BCI professionals academic or industry experience in at least one of the following categories, or both:

1. CE and related concepts: CE, Sustainability, Circular building design, DfC, Green construction, Life cycle carbon assessment of buildings, Building retrofitting.
2. IC and related concepts: Modular construction, IC, OSC, DfMA, Lean construction, Prefabrication, Building fit-outs.

A pilot survey with eight 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 (Van Teijlingen & Hundley, 2001). In addition to inquiring about the clarity and flow of the questionnaire, the participants were also asked about the readability of the online questionnaire developed using the *Qualtrics* platform, on both mobile and desktop devices. The questionnaire was refined thereafter, also to simplify the highly technical terminology and to reduce the time consumed in responding. The questionnaire was distributed globally through emails, social media platforms such as *WhatsApp* and *Facebook* and professional networking platforms such as *LinkedIn*. A total of 177 valid responses were collected through purposive sampling combined with snowball sampling as above. Table 8 presents the profile of questionnaire survey respondents.

Table 8: Profile of Panel of Questionnaire Survey Respondents

Category		Frequency (N=177)	Percentage
Profession/ Job Role	Engineer	79	45%
	Quantity Surveyor	46	26%
	Researcher/ Academic	23	13%
	Construction Manager	11	6%
	Architect	8	5%
	Facility Manager	5	3%
	Material Supplier	1	1%
	Property Developer	1	1%

Category		Frequency (N=177)	Percentage
	PhD Student	1	1%
	Building Information Modelling (BIM) Coordinator	1	1%
	Material Supplier	1	1%
Discipline/ Area of Expertise	Civil Engineering	96	54%
	Quantity Surveying	52	29%
	Architecture	9	5%
	Construction/ Project Management	8	5%
	Facilities Management	7	4%
	Environmental Engineering	5	3%
Organisation Type	Contractor	46	26%
	Public Entity	42	24%
	Consultant	35	20%
	University	31	18%
	Designer	7	4%
	Client	5	3%
	Independent (Researcher/ Professional)	4	2%
	Property Developer	4	2%
	Maintenance Research and Development	1	1%
	Manufacturer	1	1%
	Material Supplier	1	1%
Industry/ Academic experience (Years)	1-5	39	22%
	6-10	93	53%
	11-20	28	16%
	More than 20	17	10%
Engagement in CE & related concepts (Years)	No experience	31	18%
	Less than 1	61	34%
	1-5	53	30%
	6-10	23	13%
	More than 10	9	5%
Engagement in IC & related concepts (Years)	No experience	97	55%
	Less than 1	39	22%
	1-5	35	20%
	5-10	4	2%
	More than 10	2	1%
Region	Sri Lanka	82	46%
	Australia	29	16%
	United Arab Emirates	19	11%
	Hong Kong (S.A.R.)	13	7%
	United Kingdom	5	3%
	Qatar	4	2%
	New Zealand	4	2%
	Bahrain	2	1%
	Canada	2	1%
	Saudi Arabia	2	1%
	United States of America	2	1%
	Sweden	2	1%
	China	1	1%
	Ireland	1	1%

Category		Frequency (N=177)	Percentage
	Japan	1	1%
	South Africa	1	1%
	Unspecified	7	4%

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 0.969 for 36 constructs (18 DfMA constructs and 18 DfC constructs), indicating excellent internal consistency of the dataset (Brown, 2002; Cronbach, 1951). The Shapiro-Wilk (S-W) test was used to measure the normality of the dataset (Shapiro & Wilk, 1965). According to the S-W test values stated in Chapter 5 under sub-sections 5.3 and 5.4, the null hypothesis that 'the data is normally distributed' was rejected as the S-W test values of the constructs were less than the standard statistical level of 0.05 (p-value $\leq \alpha = 0.05$) (Chou et al., 1998; Shapiro et al., 1968). Further details on survey administration, descriptive analysis of DfMA and DfC constructs, and factor analysis (using EFA and FSE) are available in Dewagoda, Chen, et al. (2025).

The confirmed key constructs of DfMA (M1-M18) and DfC (C1-C18) through descriptive statistics, were subsequently analysed using PLS-SEM to quantitatively evaluate their complex interrelationships (Becker et al., 2022). PLS-SEM is particularly suited to causal-predictive modelling, balancing explanation and prediction to support both theory testing and practical recommendation (Becker et al., 2022). PLS-SEM and the development of HCM were carried out using *SmartPLS 4* software. A HCM extends PLS-SEM by modelling multidimensional constructs at higher levels of abstraction and examining their relationship with underlying dimensions (Becker et al., 2012). Hypotheses for the model were derived directly from the dynamic propositions validated through the Delphi study. This study employed the *disjointed two-stage approach* to estimate the HCM, as it simplifies the implementation and overcomes limitations inherent in *SmartPLS 4* when modelling composite formative-formative HCMs. The model was evaluated in two stages: first through measurement model assessment and then through structural model assessment. Given the centrality of these model evaluations in PLS-SEM, both are clearly discussed in Section 4. Mediation analysis was also conducted, as PLS-SEM recognises mediation when one construct intervenes between two related constructs (Hair Jr et al., 2021). This was particularly relevant given the layered relationships among DfCMA constructs as presented in Section 4.

3.3 System Dynamics Model (SDM) Conceptualisation: Causal Loop Diagram (CLD)

SDM provides a holistic means of analysing complex, dynamic systems composed of multiple interdependent sub-systems with non-linear feedback processes (Tang et al., 2019). SDM has gained prominence in CE research, given its ability to model dynamic, interdependent, and non-linear relationships that generate multiple feedback loops. The modelling process starts with the 'Model Conceptualisation Phase', which involves defining the model purpose (problem), identifying users and conceptualising system dynamics (Elsawah et al., 2017). CLDs are used to conceptualise causal and feedback structure of a system. A CLD visualises hypothesised cause-effect relationships and feedback loops, offering insight into the system structure to be modelled (Dangerfield, 2014). From an endogenous perspective, when a change in one variable propagates through the system and eventually influences the original variable, a 'feedback loop' is formed (Richardson, 2011). CLDs therefore serve as tools for representing *system feedback structures,* articulating dynamic hypotheses, and communicating the feedback mechanisms responsible for system behaviour (Sterman, 2000).

4 Results

4.1 Dynamic Propositions of Structural Relationships between DfCMA Constructs

A HCM, as an extension of PLS-SEM, represents multidimensional constructs at higher levels of abstraction and relates them to other multidimensional constructs, acting as complete mediators between higher and lower-order dimensions (Becker et al., 2012). These multidimensional constructs, referred to as 'latent variables', may be First Order Constructs (FOCs), Second Order Constructs, or higher. FOCs are directly linked to observed variables (indicators), which in this study are the DfCMA constructs (M1-M18 and C1-C18). The Higher-Order Constructs (HOCs) serve as 'endogenous constructs', meaning they are predicted by their underlying Lower-Order Constructs (LOCs), while exogenous constructs are independent variables not predicted by other latent variables (Hair Jr et al., 2021). The *disjointed two-stage approach* was used to estimate the HCM, as it produces more parsimonious models and is better suited to the composite formative-formative structure of the HCM developed in this study. Although the embedded two-stage approach offers higher accuracy (Becker et al., 2022), it was unsuitable for capturing the complexity of the composite HCM in this research. The disjointed two-stage approach was therefore implemented as outlined (Becker et al., 2022), as it is highly suitable for in modelling the composite formative-formative HCM, capturing the inherent complexity of DfCMA constructs. As the name itself suggests, disjointed two-stage approach was carried out in two stages as explained in Table 9.

Table 9: Disjointed Two-Stage Approach of HCM Estimation

Stage	Steps	
Stage I	1	Modelling the LOCs and connecting them to the antecedents (causes) and consequences (effects) of the HOCs
	2	Evaluating the measurement model of LOCs
Stage II	1	Modelling the HOCs using the latent variable scores of the LOCs from *Stage I* as the HOC indicators
	2	Evaluating the structural model of HOCs

Here, the 'measurement model' (*outer model)* refers to the components that contain the indicators and specify their relationships with the corresponding constructs, whereas the 'structural model' (inner model) represents the constructs themselves and the theoretical or logical relationships among them (Hair Jr et al., 2021). The following sub-section presents Step 2 of Stage I of the disjointed two-stage approach.

4.1.1 Evaluation of the Measurement Model of the HCM

Measurement models may be reflective, formative, or a combination of both. In a reflective measurement model, causality flows from the construct to its indicators; in a formative measurement model, causality flows from the indicators to the construct (Hair Jr et al., 2021). Table 10 summarises the evaluation criteria used for both reflective and formative measurement models used in this study.

Table 10: Evaluation Criteria of the Measurement Model of LOCs

Measurement Model	Evaluation Criteria	Indicator	Description	Sources
Reflective Measurement Model	Strength of the relationship between an indicator and its reflective construct	Outer Loading	Outer loading value of 0.5 or more is considered satisfactory in explanatory research, and 0.7 or greater is deemed highly acceptable	(Abdulai et al., 2024; Madushika & Lu, 2025; Sinha & Jayaraman Sethuraman, 2025)
	Internal consistency and reliability	Cronbach's Alpha	The threshold is typically set at 0.7, even though a minimum value of 0.5 can be tolerated in exploratory research	(Abdulai et al., 2024; Madushika & Lu, 2025; Sinha & Jayaraman Sethuraman, 2025)
		Composite Reliability	Similar to Cronbach's Alpha, it ought to be higher than 0.7	(Abdulai et al., 2024; Madushika & Lu, 2025; Sinha & Jayaraman Sethuraman, 2025)
	Convergent validity	Average Variance Extracted (AVE)	A threshold of 0.5 or above is accepted for AVE	(Madushika & Lu, 2025; Sharma et al., 2024; Zhao et al., 2013)
	Discriminant validity	Heterotrait-Monotrait (HTMT) Ratio	A value less than 0.90 is typically considered indicative of adequate	(Abdulai et al., 2024; Sharma et al., 2024; Sinha & Jayaraman Sethuraman, 2025; Zhao et al., 2013)
		Fornell-Larcker Criterion	Posits that a construct should share higher variance with its indicators than it does with other constructs within the model. Hence, in the correlation matrix, the square root of AVE for each construct along the diagonal should be higher than the off-diagonal correlation coefficients in their respective rows and columns.	(Madushika & Lu, 2025; Sinha & Jayaraman Sethuraman, 2025; Zhao et al., 2013)
		Cross-Loading	An indicator should load better on its construct compared to its loadings on other constructs	(Abdulai et al., 2024; Madushika & Lu, 2025; Sinha & Jayaraman Sethuraman, 2025)
Formative Measurement	Relative importance or contribution of an indicator to its formative construct	Outer Weight	The outer weight of a formative indicator is significant at a 95% confidence level ($\rho<0.05$). However, when the indicator weight is not significant, but the indicator loading is equal to or above 0.5, the indicator is retained	(Hair et al., 2019; Hair Jr et al., 2021)

Measurement Model	Evaluation Criteria	Indicator	Description	Sources
	Statistical Significance of the outer weight of the indicator	ρ-value	For a 95% confidence level, the value of ρ should be less than 0.05	(Hair Jr et al., 2021; Sharma et al., 2024)
		t-value	A t-value greater than 1.96 at a significance level of 95% (Two-Tailed Test) suggests that the indicator weight is statistically significant	(Hair Jr et al., 2021; Sharma et al., 2024)
	Multicollinearity	Variance Inflation Factor (VIF)	VIF values below 3 are highly acceptable, and values below 5 are generally accepted	(Bello et al., 2023; Hair et al., 2019; Hair Jr et al., 2021)

All variables except the higher-order DfCMA and the performance variables, P1-P6 are formative in nature, Therefore, reflective measurement model evaluation applies only to DfCMA and P1–P6. However, since P1-P6 each consist of a single indicator, Cronbach's Alpha, Composite Reliability, and AVE are not applicable to them. Table 11 presents the Cronbach's Alpha, Composite Reliability, and AVE of the construct 'DfCMA'.

Table 11: Cronbach's Alpha, Composite Reliability, AVE of DfCMA

Reflective Model Evaluation Criteria	Cronbach's alpha	Composite reliability	Average variance extracted (AVE)
DfCMA	0.760	0.802	0.596

All values of fall within the accepted thresholds outlined in Table 8, confirming the internal consistency, reliability, and convergent validity of the DfCMA construct. Regarding factor loadings, C1 (0.817), C2 (0.834), and C3 (0.869) demonstrate stronger relationships with DfCMA, while M5 (0.512) exhibits a moderate relationship. Table 12 presents the HTMT Ratios for the reflective constructs of the HCM.

Table 12: HTMT Ratios of Reflective Constructs of the HCM

	DfCMA	P1	P2	P3	P4	P5	P6
DfCMA							
P1	0.608						
P2	0.751	0.416					
P3	0.805	0.427	0.611				
P4	0.613	0.315	0.484	0.436			
P5	0.666	0.365	0.567	0.562	0.477		
P6	0.635	0.546	0.438	0.448	0.381	0.471	

All HTMT values are below 0.9, supporting the discriminant validity of the reflective measurement model. Table 13 presents the Fornell-Larcker Criterion values, where the diagonal values exceed the corresponding off diagonal values, further confirming discriminant validity.

Table 13: Fornell-Larcker Criterion Values of Reflective Constructs of the HCM

	DfCMA	P1	P2	P3	P4	P5	P6
DfCMA	**0.772**						
P1	0.526	**1.000**					
P2	0.660	0.416	**1.000**				
P3	0.703	0.427	0.611	**1.000**			
P4	0.561	0.315	0.484	0.436	**1.000**		
P5	0.581	0.365	0.567	0.562	0.477	**1.000**	
P6	0.545	0.546	0.438	0.448	0.381	0.471	**1.000**

The Fornell-Larcker values along the diagonal are higher than the off-diagonal values of the respective construct, further establishing the discriminant validity of the reflective measurement model. Table 14 presents the cross-loading values, demonstrating that each reflective indicator loads highest on its intended construct, thereby reinforcing discriminant validity.

Table 14: Cross-Loading of Indicators of Reflective Constructs of the HCM

	C1	C2	C3	M5	M8	C12	C17	C15	C9	M2
DfCMA	**0.817**	**0.834**	**0.869**	**0.512**	0.526	0.660	0.703	0.561	0.581	0.545
P1	0.438	0.400	0.456	0.324	**1.000**	0.416	0.427	0.315	0.365	0.546
P2	0.555	0.497	0.619	0.328	0.416	**1.000**	0.611	0.484	0.567	0.438
P3	0.571	0.602	0.585	0.384	0.427	0.611	**1.000**	0.436	0.562	0.448
P4	0.532	0.456	0.540	0.101	0.315	0.484	0.436	**1.000**	0.477	0.381
P5	0.446	0.485	0.514	0.327	0.365	0.567	0.562	0.477	**1.000**	0.471
P6	0.455	0.424	0.443	0.369	0.546	0.438	0.448	0.381	0.471	**1.000**
CM1	0.451	0.483	0.544	0.319	0.392	0.517	0.562	0.522	0.548	0.473
CM2	0.521	0.488	0.512	0.395	0.581	0.578	0.575	0.407	0.589	0.560
CM3	0.483	0.565	0.520	0.440	0.532	0.605	0.621	0.461	0.593	0.612
CM4	0.493	0.509	0.531	0.241	0.475	0.551	0.453	0.528	0.608	0.522
CM5	0.497	0.546	0.497	0.187	0.367	0.564	0.531	0.492	0.585	0.375
High Design Complexity	0.481	0.464	0.494	0.260	0.614	0.483	0.487	0.547	0.537	0.519
Low Design Complexity	0.486	0.495	0.559	0.438	0.522	0.545	0.603	0.442	0.556	0.644
C4	0.507	0.489	0.591	0.256	0.438	0.497	0.496	0.725	0.552	0.398
C5	0.487	0.540	0.548	0.236	0.357	0.598	0.514	0.580	0.557	0.346
C6	0.519	0.531	0.573	0.230	0.341	0.625	0.521	0.630	0.625	0.394
C7	0.463	0.448	0.555	0.284	0.391	0.484	0.526	0.533	0.524	0.541
C10	0.494	0.553	0.664	0.375	0.511	0.597	0.598	0.537	0.671	0.517
C11	0.338	0.386	0.438	0.473	0.379	0.503	0.455	0.302	0.479	0.366
C13	0.545	0.531	0.614	0.320	0.521	0.487	0.606	0.513	0.646	0.456
M1	0.456	0.551	0.509	0.329	0.496	0.408	0.428	0.460	0.484	0.642
M9	0.444	0.434	0.398	0.312	0.583	0.388	0.506	0.314	0.418	0.676
M11	0.375	0.346	0.354	0.127	0.304	0.338	0.358	0.361	0.410	0.332
M15	0.438	0.478	0.401	0.270	0.561	0.408	0.449	0.348	0.499	0.491
M16	0.418	0.539	0.521	0.311	0.468	0.499	0.533	0.401	0.473	0.476

There is no cross-loading as all the indicators of the reflective indicators have the highest loading on their respective construct compared to other constructs, thus confirming the discriminant validity of the reflective measurement model. The formative measurement model was then evaluated using bootstrapping with 500 sub-samples at a 5% significance level of a two-tailed test. Table 15 presents the outer weights, ρ-values, and t-values of the formative measurement model.

Table 15: Outer Weights, ρ-values, and t-values of the Formative Measurement Model

	Outer Weight	Mean	Standard Deviation	t-values	ρ-values
C18 → CM3	0.428	0.421	0.087	4.892	0.000
M10 → CM2	0.370	0.357	0.129	2.878	0.004
M12 → CM2	0.522	0.519	0.120	4.369	0.000
M13 → CM2	0.271	0.280	0.129	2.095	0.036
M14 → Low Design Complexity	0.250	0.243	0.107	2.336	0.020
M16 → High Design Complexity	0.544	0.540	0.074	7.382	0.000
M17 → CM3	0.512	0.522	0.114	4.515	0.000
M18 → CM3	0.243	0.235	0.084	2.905	0.004
M3 → High Design Complexity	0.604	0.608	0.074	8.179	0.000
M4 → Low Design Complexity	0.476	0.477	0.101	4.731	0.000
M7 → Low Design Complexity	0.448	0.447	0.110	4.066	0.000

All formative indicators have ρ-values below 0.05, t-values above 1.96 at a significance level of 95%, confirming statistical significance. For C14, C16, and C18, each being the sole indicator of their respective constructs, t-values and ρ-values are not applicable. Having completed the measurement model evaluation, the next step was to model the HOC, using Stage II of the disjointed two-stage approach. The following sub-section presents Step 2 of Stage II of the disjointed two-stage approach.

4.1.2 Evaluation of the Structural Model of the Hierarchical Component Model (HCM)

Table 16 summarises the evaluation criteria used to assess the structural model used in this study.

Table 16: Evaluation Criteria of the Structural Model of HOCs

Evaluation Criteria	Indicator	Description	Sources
The direct and linear effect of one construct on a dependent variable	Path coefficient (β)	Values are usually between -1 and +1. Coefficients closer to -1 represent strong negative relationships, while those closer to +1 indicate strong positive relationships.	(Hair et al., 2019; Hair Jr et al., 2021)
Statistical Significance of the path coefficient of the construct	ρ-value	For a 95% confidence level, the value of ρ should be less than 0.05	(Hair Jr et al., 2021; Madushika & Lu, 2025; Sharma et al., 2024)
	t-value	A t-value greater than 1.96 at a significance level of 95% (Two-Tailed Test) suggests that the indicator weight is statistically significant	(Hair Jr et al., 2021; Madushika & Lu, 2025; Sharma et al., 2024)
The variance of a dependent construct that is explained by its predictor constructs	Explanatory power (R^2)	Values are usually between 0 and 1. Values of 0.75, 0.50, and 0.25 can be considered	(Hair et al., 2019; Hair Jr et al., 2021)

Evaluation Criteria	Indicator	Description	Sources
		substantial, moderate, and weak, respectively	
The contribution of an independent variable to the overall Explanatory power (R^2)	Effect size (f^2)	Values of 0.35, 0.15, and 0.02 represent substantial, moderate, and weak, respectively	(Abdulai et al., 2024; Hair et al., 2019)

433 Table17 summarises the evaluation of the structural model in terms of Path coefficients (β), ρ-values,
434 and t-values.

435 *Table 17: Path Coefficients (β), ρ-values, and t-values of the Structural Model*

Code	Hypothesis	Path Coefficient	Mean	Standard Deviation	t-values	ρ-values	Interpretation
H1	P1 → CM5	0.104	0.103	0.075	1.384	0.166	Very small positive effect, and ρ>0.05
H2	P2 → CM5	0.356	0.353	0.085	4.205	0.000	The hypothesis is supported
H3	P3 → CM5	0.269	0.265	0.083	3.250	0.001	The hypothesis is supported
H4	C10 → CM3	0.465	0.465	0.069	6.783	0.000	The hypothesis is supported
H5	M15 → P2	-0.408	0.407	0.083	4.946	0.000	The hypothesis is supported
H6	P6 → CM2	0.560	0.562	0.071	7.874	0.000	The hypothesis is supported
H7	P5 → CM4	0.482	0.48	0.064	7.487	0.000	The hypothesis is supported
H8	M16 → CM4	0.268	0.269	0.066	4.074	0.000	The hypothesis is supported
H9	P4 → CM1	0.274	0.267	0.099	2.769	0.006	The hypothesis is supported
H10	C7 → CM1	0.465	0.474	0.082	5.651	0.000	The hypothesis is supported
H11	C11 → C10	0.603	0.6	0.064	9.378	0.000	The hypothesis is supported
H12	M9 → High Design Complexity	0.576	0.575	0.065	8.812	0.000	The hypothesis is supported
H13	High Design Complexity→ P6	-0.038	0.037	0.082	0.459	0.647	Very small negative effect, and ρ>0.05
H14	High Design Complexity→ Low Design Complexity	-0.680	0.682	0.049	13.918	0.000	The hypothesis is supported
H15	High Design Complexity → C4	-0.394	0.39	0.071	5.564	0.000	The hypothesis is supported

Code	Hypothesis	Path Coefficient	Mean	Standard Deviation	t-values	ρ-values	Interpretation
H16	Low Design Complexity → P6	0.399	0.4	0.096	4.151	0.000	The hypothesis is supported
H17	Low Design Complexity → C6	0.488	0.495	0.080	6.080	0.000	The hypothesis is supported
H18	M1 → P6	0.409	0.409	0.077	5.278	0.000	The hypothesis is supported
H19	M1 → P5	0.484	0.481	0.069	7.049	0.000	The hypothesis is supported
H20	M1 → C13	0.169	0.354	0.071	2.390	0.017	The hypothesis is supported
H21	M11 → M16	0.359	0.165	0.086	4.172	0.000	The hypothesis is supported
H22	P5 → C13	0.564	0.564	0.069	8.158	0.000	The hypothesis is supported
H23	C13 → C7	0.490	0.485	0.077	6.349	0.000	The hypothesis is supported
H24	C6 → C4	0.286	0.286	0.089	3.207	0.001	The hypothesis is supported
H25	C5 → C4	0.130	0.133	0.092	1.414	0.157	Very small positive effect, and ρ>0.05
H26	C4 → P4	0.725	0.726	0.044	16.384	0.000	The hypothesis is supported
H27	CM1 → DfCMA	0.186	0.183	0.074	2.509	0.012	The hypothesis is supported
H28	CM2 → DfCMA	0.223	0.225	0.086	2.602	0.009	The hypothesis is supported
H29	CM3 → DfCMA	0.157	0.16	0.112	1.405	0.160	Very small positive effect, and ρ>0.05
H30	CM4 → DfCMA	0.168	0.166	0.081	2.082	0.037	The hypothesis is supported
H31	CM5 → DfCMA	0.234	0.233	0.069	3.410	0.001	The hypothesis is supported

The path coefficients indicate that hypotheses H1, H14, H26, and H30 exhibit weak relationships and are not statistically significant (ρ>0.05). All remaining hypotheses are supported. The explanatory power (R^2) of the construct 'DfCMA' is 0.587, which means that the model explains 58.7% of the total variance. This represents a moderately strong level of explanatory power, consistent with the thresholds suggested by Ali et al. (2023) and Madushika and Lu (2025). Table 18 presents the effect sizes (f^2) of the independent variables.

Table 18: Explanatory Power (f^2) of the HCM

Causal Path	Effect size (f^2)
CM1 → DfCMA	0.270
CM2 → DfCMA	0.046
CM3 → DfCMA	0.062
CM4 → DfCMA	0.023

CM5 → DfCMA	0.038

The causal path between CM1 and DfCMA demonstrates a medium effect size, while the remaining paths exhibit weak to moderate effects. This implies that 'CM1 Design for sustainable and resilient building life cycle management' is a key driver of DfCMA, while CM2-CM5 exert minor, but still meaningful influence.

Having evaluated both the measurement and structural models and interpreted the structural relationships quantitatively, the next step involved identifying the unique behavioural patterns of the model through mediation analysis to enhance contextual understanding (Saihi et al., 2023).

4.1.3 Mediation Analysis of the Hierarchical Component Model (HCM)

Mediation occurs when a construct, referred to as the mediator, intervenes in the relationship between two other constructs (Hair Jr et al., 2021). According to the source, such a 'mediating effect' is expressed using the *direct effect*, which is the relationship between the related constructs and the *indirect effect*, which is the relationship between the mediator construct and the related constructs that result in mediation. Indirect effect is the mediating effect between the related constructs and is denoted as the product of the mediating path coefficients. When both the direct and indirect effects are statistically significant ($\rho<0.05$), their sum constitutes the total effect, which reflects the overall influence of the independent variable on the dependent variable (Saihi et al., 2023). Table 19 presents the hypothesised mediation relationships examined in this study.

Table 19: Hypothesised Mediation Relationships Between the DfCMA Constructs

Code	**Hypothesis**
H32	Low Design Complexity has a statistically significant mediating effect on the structural relationship between High Design Complexity and P6 Construction Productivity and Time Efficiency
H33	P5 EoL Deconstruction Potential Design for demountable and mobile modules has a statistically significant mediating effect on the structural relationship between M1 Reversible inter-module connections and C13 Design for multiple lifecycle use of modules

Table 20 presents an evaluation of H32 and H33 in terms of total effect and their significance.

Table 20: Evaluation of the Mediation Relationships Between the DfCMA Constructs

Mediation Hypothesis & Causal Hypothesis			**Direct Path**				**Indirect Path**				**Total Effect**				
			β	**SD**	**t-values**	**ρ-values**	**β**	**SD**	**t-values**	**ρ-values**	**β**	**Mean**	**SD**	**t-values**	**ρ-values**
H32	H13	High Design Complexity → P6	-0.038	0.082	0.459	0.647 >0.05	-	-	-	-	-0.309	0.311	0.072	4.297	0.000 <0.05
	H14	High Design Complexity → Low Design Complexity	-	-	-	-	-0.680	0.049	13.918	0.000 <0.05					

	H16	Low Design Complexity → P6	-	-	-	-	0.399	0.096	4.151	0.000 <0.05					
H33	H20	M1 → C13	0.169	0.071	2.390	0.017 <0.05									
	H19	M1 → P5	-	-	-	-	0.484	0.069	7.049	0.000 <0.05	0.442	0.437	0.069	6.381	0.000 <0.05
	H22	P5 → C13	-	-	-	-	0.564	0.069	8.158	0.000 <0.05					
SD Standard Deviation								**β** Path coefficient							

The results reveal a statistically significant negative total effect between High Design Complexity and P6, and a statistically significant positive total effect between M1 and C13. Because the direct path between 'High Design Complexity' and P6 is not statistically significant, the mediating construct Low Design Complexity fully mediates this relationship. In contrast, both the direct and indirect paths between M1 and C13 are significant, indicating partial mediation through P5. Based on the measurement model evaluation, structural model evaluation, and mediation analysis, the final HCM of DfCMA constructs is presented in Figure 2.

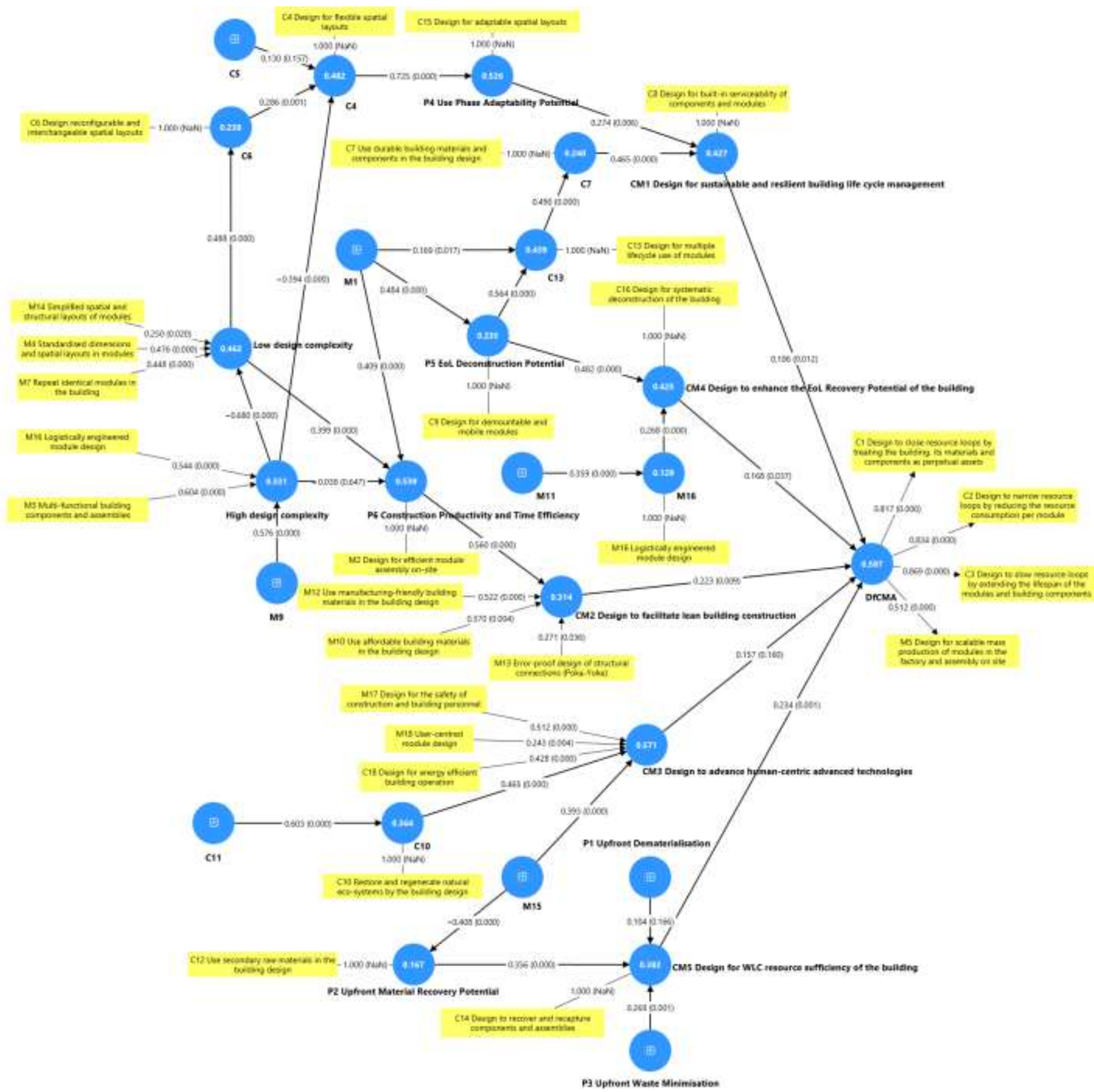
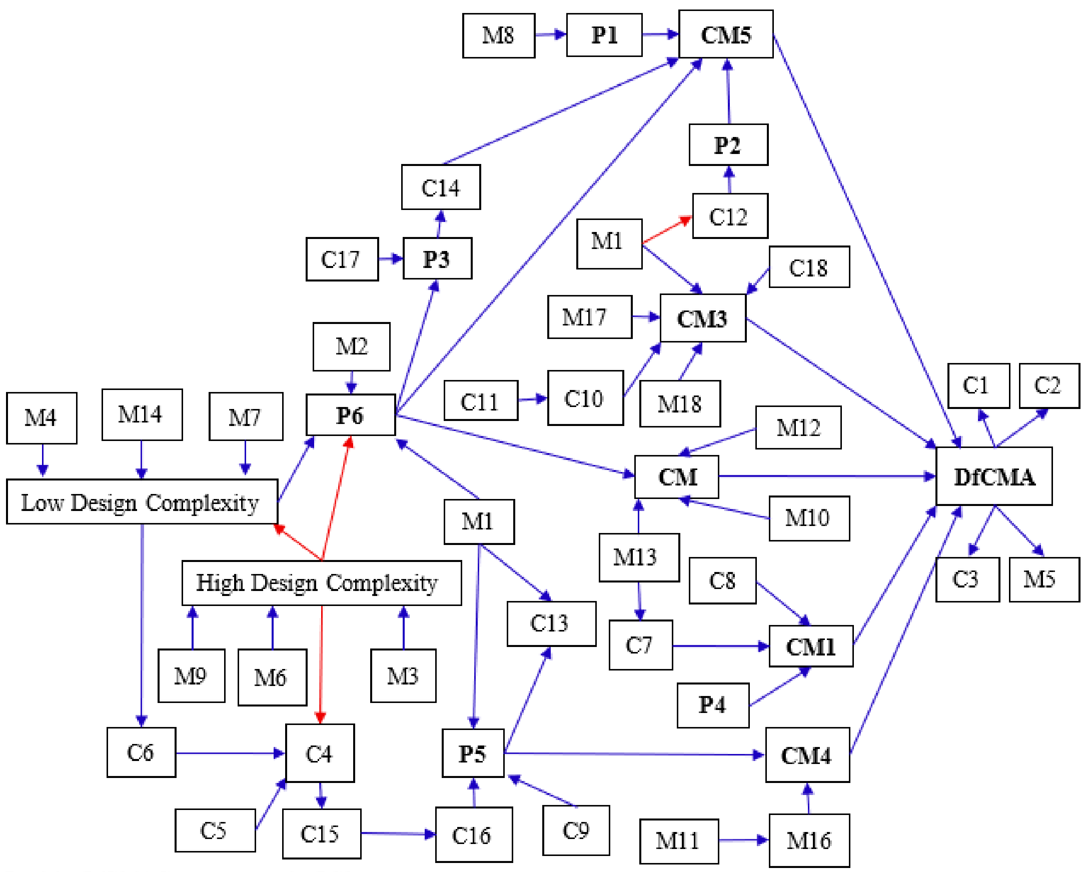


Figure 2: HCM of DfCMA Constructs in the BCI

4.2 Causal Loop Structure of DfCMA Constructs in the Building Construction Industry

The next step was to develop the CLD informed by the Delphi study findings and the HCM (PLS-SEM). Constructing the CLD requires careful system boundary definition to maintain an endogenous perspective. This includes identifying the 'endogenous variables' within the system boundary, 'exogenous variables' lying outside the system boundary and the 'excluded variables' that are not closely related to the problem in focus. The problem focus guiding this CLD is, 'How can the synergistic benefits of DfMA and DfC be effectively leveraged across the WLC of a modular building?'. Accordingly, the DfC constructs C1-C18, DfMA constructs M1-M18, performance variables (P1-P6), DfCMA group variables (CM1-CM5, DfCMA) and their interrelationships are treated as endogenous variables. Sustainability-related parameters such as overall wellbeing of stakeholders, energy performance, global warming potential, and water consumption are considered exogenous variables. EoL recovery potential and waste minimisation are also considered exogenous variables, along with contextual factors such as governing regulations, political landscape, consumer behaviour, cultural tendencies, technological innovations, and economic infrastructure, which are inherently uncontrollable and unpredictable. Organisational and managerial practices of stakeholders within the CICVC are excluded from this model, as the research adopts the perspective of the building system, not individual actors. Essential requirements of modular building systems, such as health and safety, structural integrity, and client satisfaction in quality and aesthetics, were assumed to be intransigent in developing the model. Based on the established cause–effect relationships and the defined system boundary, the CLD was developed and is presented in Figure 3.



Legend			
→	Positive Causal Link	→	Negative Causal Link
C1-C18	DfC Constructs (Table 1)	**M1-M18**	DfMA Constructs (Table 2)
P1-P6	Performance Variables	**CM1-CM5, DfCMA**	DfCMA Group Variables

Figure 3: CLD of the Key Constructs of DfCMA in the BCI

5 Given that the CLD is developed considering a high-rise residential PPVC project, focusing on a corner apartment modules' envelope, including connections, load-bearing walls, roof slab and floor slab, assuming to comply to BaaS model, the resultant outputs

are highly contextual-, and project-specific as the model behaviour is an artifact of the specific project's conditions. Furthermore, contextual differences may affect the 'constructs' of DfC and DfMA, as each building construction project is unique. However, this study identified indispensable DfC and DfMA constructs commonly perceived in CE and IC through the questionnaire survey to enhance the generalisability of the findings globally. The findings provide valuable insight into regions with nascent IC practices on systematising the design process by integrating DfMA principles, followed by DfC synergy. Even though the CLD outputs may not be directly transferable to other contexts (for example, mature markets of IC such as in China), contextualised transference of case study findings, and replication by recognising similar (even though not identical) patterns nuanced in a different case is recommended.Discussion

In establishing how the key constructs of DfCMA interact dynamically across the WLC of modular buildings, this study sought to uncover the practical mechanisms through which circularity and productivity can be jointly advanced in IC. The structural relationships identified through the Delphi study and validated through PLS-SEM provide a foundation for interpreting how design decisions influence dematerialisation, recovery potential, waste minimisation, adaptability, deconstructability, and construction efficiency in practice. Against this backdrop, the following discussion synthesises these findings and highlights their direct implications for designers, manufacturers, policymakers, and project teams seeking to operationalise circularity within modular building systems.

Redesigning a building to reduce overall material input (M8) directly enables delivery with lower extraction demands, thereby contributing to upfront dematerialisation (P1). In practice, this means that strategies such as multi-purpose spaces, shared functions, and intensified functional use allow designers to achieve the same performance with fewer materials. Similarly, substituting physical building functions with virtual services such as remote working hubs or digital service platforms can eliminate or reduce the need for new physical space, further supporting dematerialisation (Arup, 2016). Secondary raw materials recovered from existing building stocks through recycling, refurbishment and remanufacturing (C12) contribute to the upfront material recovery potential (P2) of new buildings. Although consumer purchase intention strongly influences the uptake of secondary materials (Ding et al., 2023), their use can substantially reduce embodied carbon and resource extraction. Practically, this underscores the need for procurement policies and client education that normalise secondary materials as high quality, compliant alternatives. The 'waste hierarchy' of CDWM prioritises waste prevention over reuse, recycling, recovery and disposal (Sharma et al., 2022). Designing out waste (C17) therefore becomes a primary strategy for achieving upfront waste minimisation (P3). While C12 supports recovery potential, designing buildings so that components can be recovered EoL contributes to CM5-Design for WLC resource sufficiency. This reinforces a practical insight: designers must consider both the 'front end' (material input) and the 'back end' (material recovery) of the building life cycle to achieve circularity.

Although designing for safety (M15) positively influences CM3, it can negatively affect the use of secondary materials (C12) due to stringent quality and safety regulations. For example, DS.10 noted that the EU's REACH regulation may restrict recycled materials with unknown chemical compositions. This highlights a practical tension: safety compliance can unintentionally hinder circularity, suggesting the need for material passports (Kedir et al., 2023; Leising et al., 2018) and transparent supply chain documentation updated throughout the building life cycle (Munaro et al., 2019; 2021). CM3-designing to incorporate human centric advanced technologies, emphasises the importance of integrating users and workers into technological transitions (Golovianko et al., 2023). M18 focuses on end users, who are critical actors in CE adoption (Ding et al., 2023), while M17 emphasises safety for construction and EoL workers. DS.7 highlighted that innovative energy efficiency strategies can conserve resources, reinforcing the positive causal link with CM3. Practically, this means technology adoption must be paired with user centred design and workforce training to ensure circularity gains are realised. Flexibility in the BCI refers to a building's ability to adapt to changing user needs (Zairul, 2021). The positive causal link from C4 to C15 indicates that flexible spatial layouts enable buildings to change capacity or function. Designing for adaptable layouts (C15) increases use phase adaptability potential, while reconfigurable components (C5, C6) enhance flexibility. Kinematic aids (Omrani & Iordanova, 2024) further support this adaptability. Practically, this means designers should prioritise modular, reconfigurable systems to extend building life and reduce the need for new construction. Reversible inter module connections, as promoted by the BAMB project (Durmisevic, 2018), support reversible configurations and increase EoL deconstruction potential (P5). M1, a core DfMA enabler, also increases deconstructability (Obi et al., 2023). Relocatable modular units (C9) further enhance deconstructability, enabling rapid assembly and disassembly (Kyrö et al., 2019). DS.12 emphasised that steel is a favourable material for modular construction due to its lightweight and durability, supporting the positive link from M11 to M16. Practically, these findings highlight that designing for deconstruction is not an abstract CE principle, it directly improves logistics, reduces EoL costs, and enables material recovery.

The introduction of High Design Complexity and Low Design Complexity reflects expert insights from the Delphi study. High design complexity competes with low complexity and reduces construction productivity and time efficiency (P6). Conversely, designing for efficient module assembly (M2) increases P6. Reversible inter module connections, typically dry joint systems, accelerate on site assembly (Pan & Zhang, 2023). Practically, this means design simplification and standardisation are essential for both productivity and circularity. *Lean construction* aims to maximise upfront value (Benachio et al., 2020), which is enhanced by affordable materials and error proofing strategies such as Poka Yoke (DS.4), confirming the positive link from M13 to CM2. Manufacturing friendly materials increase resource productivity, while simplified layouts reduce design complexity and enhance reconfigurability. Standardisation, a core DfMA principle, reduces design complexity and supports modular interchangeability. However, integrated assemblies (M6), multifunctionality, and modularity can increase design complexity, forming positive links with High Design Complexity. Practically, this highlights a key trade off: designers must balance modularity and multifunctionality with simplicity to avoid undermining productivity and adaptability. DfCMA bridges CM1-CM5 with C1, C2, C3, and M5. C1-C3 reflect the core DfC principles of narrowing, slowing, and closing resource loops, while M5 introduces scalability, a key DfMA dimension. Practically, this means DfCMA provides a unified framework for aligning productivity and circularity goals, which are often treated separately in practice.

Construction clients, investors and users, make the most influential decisions in the CICVC (Geldermans, 2016). Therefore, reforming business models toward Product Service Systems (PSS) and extending stewardship across the building life cycle are essential. Public sector leadership can accelerate this shift by mandating circular procurement (Alhola et al., 2019). Legislation can act as a catalyst for CE transition (Scipioni et al., 2021), while regulatory standards can streamline implementation (Andersen et al., 2019). Practically, this means policy alignment and client driven demand are critical enablers of circular modular construction. Comparing the Delphi and PLS-SEM findings reveals that although the causal links P1 → CM5 (H1), High Design Complexity → P6 (H13), C5 → C4 (H25), and CM3 → DfCMA (H29) were validated qualitatively, they were not statistically significant. These links were retained due to strong theoretical grounding and expert consensus. For example, 'P1 Upfront Dematerialisation' results in 'CM5 Design for WLC resource sufficiency of the building' as evident in existing literature as well as ascertained through the Delphi Study and hence retained to be considered in the CLD to be further evaluated using SDM. Similarly, higher design complexity causes the construction productivity and time efficiency to decrease, resulting in a negative causal link between them. Kinematic aids that can move or change the position of the components support C6, enhancing the flexibility of the design (Omrani & Iordanova, 2024). Hence, reconfigurable and interchangeable spatial layouts and components that can be upgraded or modified cause an increase in the flexibility of a building, endorsing the positive causal links from C5 to C6 and C6 to C4. Even though a weak or non-significant path, "*may not warrant managerial attention*", evaluation of the relative importance of relationships is critical in drawing conclusions (Hair Jr et al., 2021, p.197). The HOC includes indicators in addition to causal links from Stage I of the disjointed two stage approach, reflecting the rationale that while LOCs form the HOCs, the indicators measure unique aspects not fully captured by LOCs.

6 Conclusions, Limitations and a Way Forward

This study presents the findings of an ongoing research effort to develop a holistic framework for synergising DfC and DfMA to advance both productivity and circularity in the BCI. The resulting, DfCMA proposes ways to design modular buildings that can be efficiently manufactured in factory environments while also narrowing, slowing, and closing resource loops across the whole building life cycle. In doing so, DfCMA positions modular construction not merely as a productivity-enhancing method, but as a viable pathway toward a circular built environment. While DfCMA benefits from the complementary and shared values of DfC and DfMA, the integration of these two paradigms also introduces competing priorities that give rise to complex interactions and interdependencies. Capturing this complexity requires a modelling approach capable of representing dynamic behaviour, feedback loops, and system wide consequences. SDM is therefore an appropriate and powerful method for conceptualising and analysing the DfCMA system. As the first and crucial step of SDM, this study developed a CLD to conceptualise the empirically-supported structural relationships between DfC and DfMA constructs. Complementing this, PLS-SEM was used to develop a HCM, quantitatively establishing the causal paths between DfCMA constructs. The study pioneers the use of a comprehensive methodological triangulation combining Delphi based expert consensus with quantitative modelling to distinguish correlation from causation and to reveal the underlying systemic structure and feedback mechanisms with greater accuracy.

The current study makes several important contributions. First, it provides the first known empirically validated causal architecture of how DfC and DfMA interact dynamically within modular construction. This offers immediate practical value as designers, manufacturers, and project teams can now identify which design decisions most strongly influence dematerialisation, adaptability, deconstructability, and construction efficiency. Second, the study offers policymakers and clients a clearer understanding of where regulatory support, procurement reform, and business model innovation can most effectively accelerate circularity in modular construction. Finally, the CLD and HCM together form a foundational systems level understanding that can guide strategic decision making across the construction value chain. The next phase of this research will involve developing a SFD and simulating the SDM. This will extend the contribution from structural understanding to dynamic prediction. The SDM will allow practitioners to test 'what if' scenarios such as increasing standardisation, mandating material passports, or adopting PSS business models before implementation. It will also quantify long term impacts on resource flows, waste generation, construction time, and recovery potential. Ultimately, the SDM will serve as a decision support tool for organisations seeking to operationalise circularity at scale and for policymakers aiming to design effective CE interventions.

Several limitations should be acknowledged besides the useful implications of this study. This study is limited by the high number of hypotheses, which may be seen to complicate the CLD in terms of readability and traceability, and by its substantial reliance on expert judgement some causal links appear more deterministic than the underlying evidence warrants. While the sample size of this study is adequate for detecting medium-to-large effects, it may lack sufficient power for small effect sizes and for conducting multi-group analyses. Hence, future studies with larger samples are encouraged to enhance the model stability and to explore potential moderating effects across different contexts. Decision-making regarding the optimal level of synergy between DfC and DfMA is highly project- and region-specific, shaped by stakeholder priorities, market conditions, regulatory frameworks, and financial structures, none of which were incorporated into the current CLD. In addition, the performance variables used in the DfCMA modelling are not exhaustive; future studies could extend these to include end-of-life waste minimisation, recovery potential, use-phase recovery potential, water consumption, energy performance, and global warming potential across all life-cycle stages. The CLD developed in this study is heuristic and conceptual, intended to provide insight into dynamic behaviour rather than to quantify impacts, making quantitative simulation through System Dynamics Modelling a necessary next step. Finally, the study relies on expert judgement due to the absence of empirical datasets on circular modular buildings; although expert consensus strengthens validity, future research should incorporate empirical data as circular modular construction becomes more widely adopted.

Moreover, this study lays the conceptual and empirical foundation for a unified, systems-based approach to circular modular construction. By advancing both theoretical understanding and practical applicability, it positions DfCMA as a promising framework for transforming the BCI into a more resource efficient, productive, and circular sector. The forthcoming SDM simulation will further enhance this contribution by offering predictive insights and actionable guidance for real world implementation.

7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8 Author Contributions

Conceptualisation: TN, MK, JC, AE, KD

Formal analysis: KD

Methodology: TN, MK, JC, KD

Project administration: TN, MK, JC, AE

Supervision: TN, MK, JC

Resources: AE

Writing – original draft: KD

Writing – review & editing: AE, MK, TN, JC

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11 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.

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