The Adoption of Circularity in Modular Construction in Developing Countries Using System Dynamics Approach

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Masters of Science in
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Thesis Supervisor: Dr. Khurram Iqbal Ahmed Khan

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THESIS ACCEPTANCE CERTIFICATE

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Date: 13 AUG 2024

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Titled : **The Adoption of Circularity in Modular Construction in Developing Countries Using System Dynamics Approach** be accepted in partial fulfillment of the requirements for the award of degree with (B+ Grade).

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No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the Department of Construction Engineering and Management in partial fulfillment of the requirements for the degree of Master of Science in Field of Construction Engineering and Management (CEM), at School of Civil and Environmental Engineering (SCEE), National University of Sciences and Technology (NUST), Islamabad.

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This thesis is dedicated to my parents and respected teachers with heartfelt gratitude!

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ABSTRACT

A country’s economic development fundamentally relies on its construction industry that is notably resource intensive and generates extensive amounts of waste leading to numerous environmental impacts. Wherefore, modular construction (MC) is known to instigate circular economy (CE) for the sector’s circularity gap to be reduced. But there is only a limited literature available focusing on their significant combined effect. Hence, the following study aims to facilitate the convenient adoption of circularity in modular construction practices. A system dynamics model (SDM) was prepared for this purpose. The research initiates with a keen literature review, content analysis and preliminary survey to sift down twenty notable factors for implementation. Then through a detailed questionnaire survey and opinions of experts’ from developing countries, the interconnectivity and functionality of these factors were established. To address the complexity of these interactions, a systems thinking approach was employed. Subsequently, a causal loop diagram (CLD) and influence matrix (IM) were prepared to evaluate their intensity and polarity. One balancing loop and five reinforcing loops constituted the CLD. The SDM formulated hinged upon the CLD and IM was simulated for a period of five years. The SDM essentially had four stocks: “Development of environmental policies”, “Proactive planning for circular MC”, “Collaboration of project team” and “Circular use of recourses”. To contemplate the converging effect of the system, an additional stock named “Adoption of Circular MC” was introduced. The outcomes suggested the escalated implementation of circular MC over time. Furthermore, the intricate interactions among the factors and their impacts on the system were successfully portrayed by the CLD and consequent SDM. Such illustrations could help the industry practitioners focus on the most vital of the factors and to make knowledge-based decisions when envisioning a circular modular project.

Keywords: Sustainable Construction; Modular construction; Circular economy; System Dynamics; Causal Loop Diagram

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CHAPTER 1:INTRODUCTION

1.1 General

Architecture, Engineering, and Construction (AEC) is the field that performs a notable role in contributing to both global warming and various environmental effects (Edenhofer et al., 2015). Similarly, the finite natural resources utilized as construction materials are progressively dwindling due to continuous extraction. Additionally, the production of waste during construction due to human activities is growing, and there is limited progress being made to reduce this impact (Hossain et al., 2020; Ogunmakinde et al., 2022). This increasing level of material extraction has diminished the global circularity. It was 9.7% in 2018, 8.6% in 2020 and further reduced to 7.2% in 2023 (Circular Economy Foundation, 2023).

Modular construction is a transformative approach to turn traditional site-based construction into a value centric production method. This approach can achieve higher quality, productivity, safety and sustainability (Pan et al., 2018).Increasing adoption of such offsite construction (OSC) methods is a prominent shift and emerging trend despite of the fact that the construction sector is characterized by fragmentation, conservatism and a slow uptake of modification and novelty (Ruparathna et al., 2013).

Taking a step further, the circular economy (CE) looks at resources in a continuous cycle. With the principles of CE, versatile buildings designed for adaptive reuse and modularity offers efficiency and health benefits (Çimen, 2021).

In the past few decades, the concept of CE has gauged popularity among industrial players, academics as well as policymakers. Based on the principles of cleaner production and resource preservation, CE is a holistic approach that encompasses the synchronized development of processes, products/services and business models. This approach aims to balance economic growth and environmental protection (McKinsey, 2015). Consolidating CE principles into construction practices with special focus upon modular construction is a viable solution to address environmental challenges in the construction industry (Yu, Junjan, et al., 2022). Embracing circular construction practices and new business models is crucial to mitigate the impact of construction industry on the growing global circularity gap (Wuni et al., 2022).

1.2 Problem Statement

Building sector still is in the primitive stages of adopting the notion of circular construction (Ossio et al., 2023). While policymakers, practitioners and academics are discussing modularization and CE in the construction industry. But these are often discussed in isolation and not together. Yet, the integration of these two is often underexplored and not universally proven across all cases (Machado et al., 2021). Recognizing this interdependence is crucial as modularization is an enabler of CE principles and can bring about a significant transformation in the lifecycle of building industry (Mignacca et al., 2020). Hence, Illankoon et al. (2023) urged that the future research on CE should be directed towards innovating business models in circular construction. In particular, construction industry is well suited for the application of CE frameworks, owing to its split processes and the escalating incorporation of ecofriendly products along combined with emerging technologies (Norouzi et al., 2021).

Besides, a few researchers undertook the integration of modular construction and circularity as a complex matter. When it comes to CE implementation, Çimen (2021) emphasizes that there is a growing need for a system dynamics approach. This method facilitates a thorough comprehension of the urban transition process, particularly when examining the effects of multiple regulatory policies. Hence, the objective of this study is to tackle the limited extent of combined literature of circular modular construction by acknowledging the involved complexities due to feedback loops, nonlinear relationships, and time delays (Chaerul et al., 2008).

1.3 Research Objectives:

The research questions thus arise are as below.

i. What could be the potential factors influencing the adoption of circular modular construction in developing countries?

ii. What significance, interconnectivity, and functionality do these identified factors have?

iii. In what way a system dynamics model (SDM) could address the complexity in adoption of circularity in modular construction to promote sustainability?

1.4 Research Methodology

The adopted methodology for the research is presented in Figure 1.1 below.

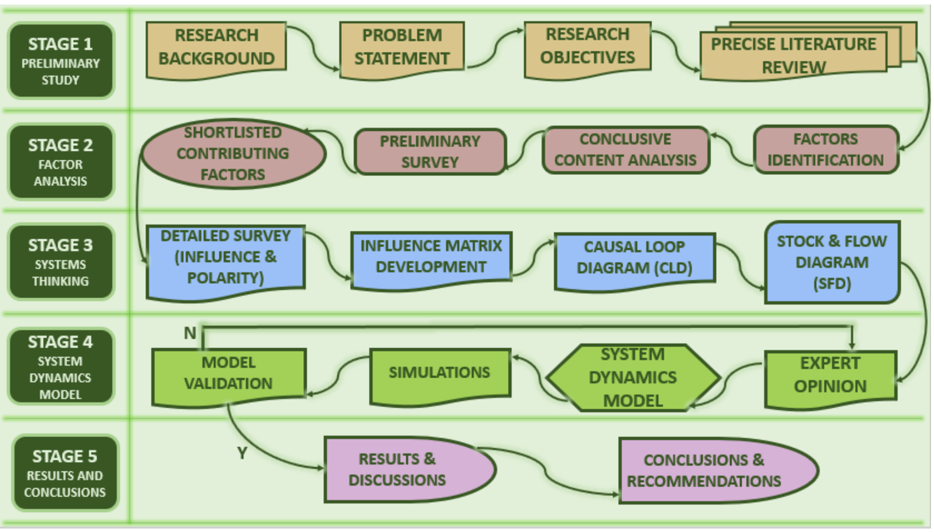


Figure 1.1: Research Methodology

This study examines the impact of key elements on the successful adoption of circular practices in modular construction. Fig 1.1 presents an organized overview of the research methodology utilized in the study. The study consists of five stages. In the first stage, a literature review was conducted to identify the research gap and organize the problem statement, leading to the formulation of research objectives. Subsequently, a detailed literature review was conducted to identify the influencing factors.. Details of which are included in chapter 2 of this thesis. Stage 3 involves the development of causal loop diagram based on the influence matrix derived from detailed questionnaire survey. Guided by the expert opinion, stage 4 is marked by the establishment of a system dynamics (Geissdoerfer et al.) model and its validation. A successful model validation proceeds towards the results and conclusions i.e. stage 5. However, an unsatisfactory SD model reverses the process back to expert opinion stage.

1.5 Thesis Organization:

The summary and organization of the research are delineated below.

Chapter one lays out the issue at hand, along with an informative introduction and detailed description. This initial chapter outlines the introduction, reviews prior studies, articulates the problem statement, and sets forth the objectives. It also outlines the study methodology designed to accomplish the research's aims and objectives. Subsequent chapters offer a more comprehensive examination.

The second chapter focuses on the literature review, presenting the work conducted by various researchers about circular economy and modular construction focusing on their integration and collaboration. These researchers employ various methodologies to accumulate all the data available worldwide regarding the said subject and try to reach a viable solution. A total of 30 influencing factors have been identified from previous literature which will be put through a system thinking approach to give an appropriate model for adoption of circular modular construction.

The third chapter discusses the research methodology in detail starting from data collection to the development of system dynamics model. All the intermediate stages are meticulously documented. The fourth chapter includes the results obtained from various stages of research scheme and deliberately explained the outcomes. Finally chapter 5 of thesis concludes the quantitative results along with the prospects and recommendations.

1.6 Significance:

The notion of Modular construction has garnered widespread recognition as an environmentally sustainable construction technique, largely due to its positive implications for environmental protection. One of the crucial facets of modularity is its effect of on curbing construction waste generation, along with the consequent processes of sorting, reutilization, recycling, and proper disposal for waste management (C. Z. Li et al., 2014). Construction industry, at present, is the world's largest consumer of resources and raw materials (Benachio et al., 2020), therefore, modularity in construction practices is the most promising technique to tackle this situation.

CE aims at decoupling economic growth from natural resources depletion thus mitigating environmental damage caused by human activity (Bressanelli et al., 2019). The ultimate aim of CE is "to optimize the benefits from resources in active use" (Kalmykova et al., 2018). According to Pan et al. (2020), 46 – 87% less waste has been generated by circular MCPs during onsite execution, resource utilization as less as 84.7% (Tam et al., 2007), resource exhaustion reduced by 35.82%, 60–68% less onsite consumption of energy, 66 –70% less use of water, ecosystem damage 3.47% lesser (Cao et al., 2015), noise pollution 7–10% lesser, and air pollution 25 –50% lesser (Pan et al., 2020). Hence, on the way of substantially mitigating the impact on environment and ecological footprint of the construction sector, circular MC can really make a difference, meanwhile delivering cost-effectiveness and financial savings to various parties involved in projects.

1.7 Relevance To National Needs:

A renowned French proverb translates to "If construction moves, everything moves." The construction industry holds a prominent position globally, making substantial contributions to the Gross Domestic Product (GDP) and Gross National Product (GNP) of many countries. Its significance extends beyond its sheer scale, encompassing its role as a pivotal driver of economic progress. Remarkably, the construction sector ranks as the swiftest expanding domain within the international market, exerting substantial influence as a prime catalyst for growth in developing economies (Maqsoom et al., 2020). Regrettably, in Pakistan, the construction sector suffers from neglect and disorganization, burdened by heavy taxation due to the prevailing perception of construction as a luxury. While sustainability issues are gaining prominence worldwide, Pakistan faces an escalating challenge in this regard. The absence of adequate education, coupled with the depletion of natural resources and ongoing economic growth, intensifies the risk of significant environmental threats (Zhang et al., 2021). For a considerable duration, the sector of brick kilns has been widely regarded as the primary static source to environmental pollution (Rauf et al., 2022). The increasing extraction of raw materials for expanding cement production results in the depletion of non-renewable resources, particularly limestone. (Mohamad et al., 2021).

Pakistan, as a developing nation, is grappling with a swiftly expanding population. Simultaneously, it confronts significant economic and energy-related difficulties (S. Khan et al., 2022). With a population of 220 million, Pakistan ranks as the fifth most populous country globally. Notably, the construction industry contributes to 2.53% of the nation's Gross Domestic Product (GDP) according to the Economic Survey of Pakistan (Board of Investment, 2023). Therefore, efforts to improve the construction industry will significantly impact Pakistan's overall economic and environmental development.

CHAPTER 2:LITERATURE REVIEW

This chapter offers a brief introduction to modular construction and the circular economy individually, followed by an overview of circular modular construction to enhance understanding of the research topic. The current body of literature focusing on circular modular construction has been examined to pinpoint the factors that influence the adoption of circular MC. The research approach and outcomes of the previous research along with the way current research brings novelty have also been outlined in this chapter. Hence, this chapter consolidates all the necessary information to establish a robust groundwork upon which the entire study is conducted.

2.1 Modular Construction

Construction becoming modular stands out as a unique off-site construction technique that incorporates principles of modularization, modularity, lean production and (DfMA) design for manufacture and assembly. It aims to deliver cost savings during the construction phase (Wuni et al., 2020a). Pan et al. (2018) reinforced that (MiC) modular integrated construction is a transformative construction method that takes the traditional segregated onsite construction process and turns it into a cohesive yet value driven production of pre-fabricated modules in a factory setting and assembling them at site. Construction Industry Council (2023) also declared MiC as an innovative construction technique and technological advancement. Pan et al. (2018) calls MiC as the highest end of prefabrication, embodying the amplest integration of value-added, factory-manufactured pre-finished units

2.2 Circular Economy

The worldwide AEC sector is reshaped by the state-of-the-art digital technologies along with a strong focus on sustainability. Notably, the adoption of a CE strategy is increasingly being recognized as a viable way out of these pressing environmental concerns like depletion of natural resources, emissions of greenhouse gases as well as construction and demolition waste management (Ogunmakinde et al., 2021). Thus, CE paradigm presents a striking opposition to the linear economy's model of "take-make-dispose". It continuously strives to minimize the waste and extend the usefulness of products by emphasizing proficient design with judicious resource utilization (Charef & Lu, 2021). CE is defined as a: “Deliberately engineered rejuvenating or regenerative industrial system. It focuses on restoration, reliance on renewable energy, discourages the practices that suppress reuse and elimination of waste to replace the notion of "end-of-life” while considering it as a business model (Ellen MacArthur Foundation, 2013a).

CE closes the resource and material loop to enhance waste reduction. This concept has been steadily gaining momentum as a promising approach towards attaining sustainable development (Ogunmakinde et al., 2022). In the construction industry, the conventional approach often adheres to the linear economy (LE) model, characterized by the linear progression of materials production and consumption. This has led to a substantial circularity gap in the construction industry due to the dominance of site-based construction methods that follow the traditional “take-make-waste” approach inherent in a linear economy (LE)

(Norouzi et al., 2021). In this way, CE simply goes beyond reducing ill-effects to envision an entire transformation into a rejuvenating and regenerating production system. This shift guides materials' cyclic mobility so as to lead less waste (Ghisellini et al., 2017).

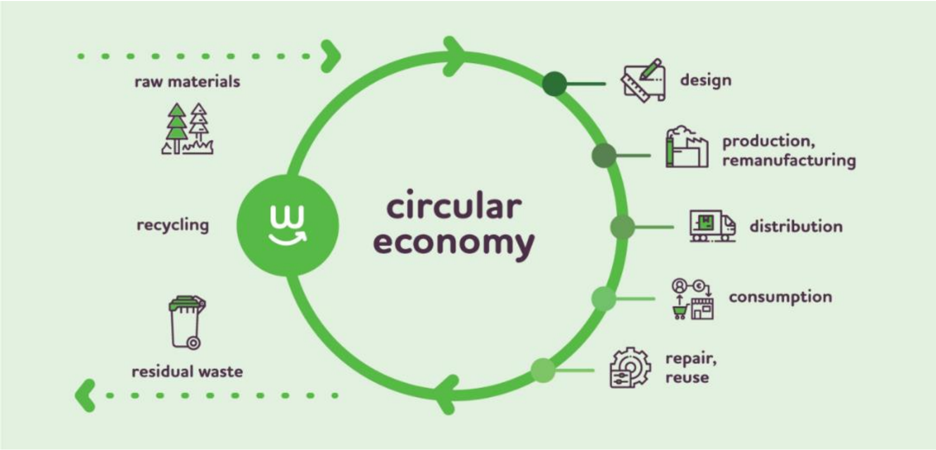


Figure 2.1: Circular Lifecycle of Resources

2.3 Circular Modular Construction

Modular construction (MC), when seamlessly incorporates circular economy principles into its core goals becomes circular MC. Necessarily, emerging as a sustainable construction approach wherein value-enhanced modules when intentionally conceived and produced within an offsite facility and are transferred to the site for final assembling. This process facilitates a continuous construction, utilization, deconstruction, reuse and recycling loops eventually returning to the material pool for subsequent construction endeavors (Ellen MacArthur Foundation, 2021). Circular MC practices encompass modular building methods that are strategically formulated, overseen, and executed as per CE principles.

(Kyrö et al., 2019). Circular MC practices are heralded as premier sustainable construction methods due to their ability to detach construction lifecycles off the depletion of resources by conceptualizing buildings that are virtually free of waste (Norouzi et al., 2021).

The quintessentially distinct characteristic of circular MC practices lies in the domain of design decisions. A meticulously devised design of a circular modular construction project (MCP) promotes the potential for reutilizing, deconstructing and recycling construction materials and building components. This mandates a prudent choice of material constituents, design specifications and standardized components to facilitate the eventual sorting, separation or repurposing of building elements as soon as their lifecycle ends. (Wuni et al., 2022).

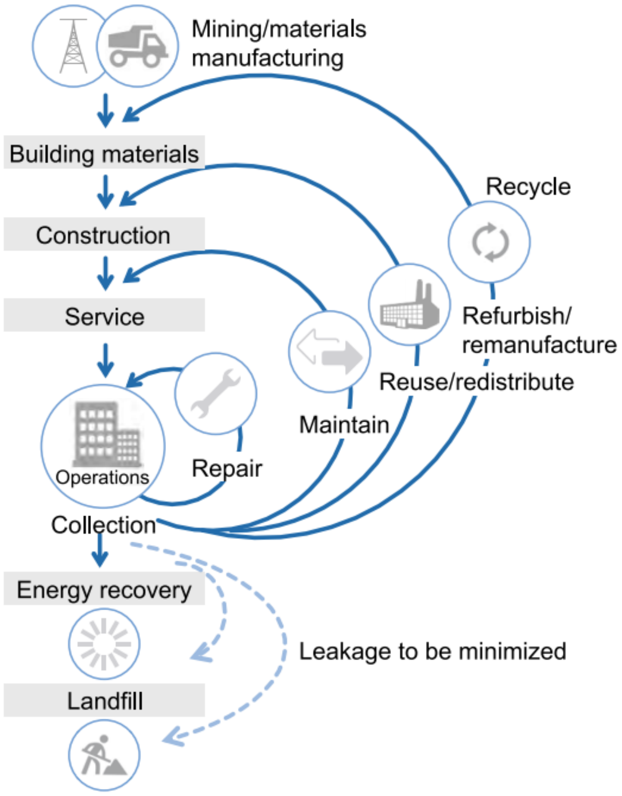


Figure 2.2: Circular Construction Lifecycle

2.4 A Global Paradigm Shift

Over the past four decades, scholars have conducted extensive research into the concept of sustainable construction (Yi et al., 2021). However, Modular Integrated Construction (MiC) has garnered significant attention as a compelling subject of research over the past decade (Abdelmageed et al., 2020). Numerous researchers have underscored the advantages and merits of modular construction i.e. Cheng et al. (2015) explored how modularization can reduce construction and demolition waste, improve the deconstruction process, and thus support the achievement of a closed-loop material cycle; European Environment Agency et al. (2017) highlighted that modular construction offers several benefits, including reduced waste generation in a controlled factory environment compared to traditional construction sites. This leads to less material transport, resulting in reduced emissions. Additionally, modular construction allows for deconstruction, moving, and renovating modules to be used again, thereby lowering the requirement of raw materials and energy. The approach also allows for the potential for repairing or altering components without jeopardizing the fundamental building structure, among other advantages.

A review study carried out by Hossain et al. (2020) with the aim of identifying the ramifications, factors to consider, contributions, and hurdles linked to the integration of Circular Economy (CE) principles in the construction sector. These challenges encompassed aspects such as designing, choosing materials, managing the supply chain, business models, dealing with uncertainty and risk, fostering collaborative efforts, enhancing knowledge and comprehension, aligning with pertinent policies, integrating the concept of urban metabolism, and developing methodologies for evaluating CE implementations. Çimen (2021) conducted the inaugural comprehensive examination of Circular Economy in the Construction and Built Environment (CBECE) domain. The aim was to showcase the evolution and multifaceted nature of CBECE literature, to assess the maturity of existing literature, identify research gaps, and shed light on areas that have received limited attention, and to emphasize significant discoveries, critical analyses, and potential directions for future research. Wuni et al. (2022) undertook a comprehensive approach, including a concentrated literature review, consultations with field experts, a questionnaire survey targeting industry practitioners and the following analysis. This comprehensive methodology aimed to identify the key success factors for integrating circular economy principles into modular construction projects within the context of Hong Kong. Zhuang et al. (2023) present an innovative approach using a topological interlocking system to design reusable modular components, with the goal of enhancing sustainability. By integrating CE strategies focused on reusability with this innovative system, their research delves into the feasibility of incorporating reusable modular components within sustainable construction practices. Garusinghe et al. (2023) identified nine key challenges in modular construction to achieve sustainability and highlighted all the Circular Economy 9-R principles that could address these issues. This underscores the importance of a holistic approach by logically integrating modular construction and circular economy principles. As a result, thirty implementation solutions were identified to foster the potential of CE principles to address the challenges and the problems in MC.

2.5 Critical Success Factors for Adoption of Circular MC

Limited scholarly literature directly focuses on the factors critically influencing the successful management and implementation of circular MCPs. Nevertheless, a substantial body of work exists that deals with critical success factors for CE in the construction sector and traditional MCPs. These can be essentially adopted for circular MCPs as well (Wuni et al., 2022). Therefore, a total of 30 critical factors have been identified from the existing literature which can contribute towards the successful implementation of circular MC.

Multiple researchers have stressed upon the fundamental principle of raising insight about CE and MC in order for its uptake and realization i.e. Prendeville et al. (2018) emphasized the need for development of knowledge by gathering information, spreading awareness and educating all the stakeholders involved in construction industry. Similarly, Wuni et al. (2020a) highlighted the importance of education, knowledge and skill building as strategies to overcome knowledge barrier in adoption of MC.

Norouzi et al. (2021) showed that a successful circular MCP requires collaboration and insights from all stakeholders in the supply chain. This collaboration is the key because each tier of the chain plays a part. García et al. (2017) stressed that stakeholders and project participants need to be prepared for frequent coordination meetings to integrate offsite and onsite construction and work packages in a coherent manner. In design-build type of integrated project delivery, setting up repetitive project teams can help implement circular MCPs. This approach promotes continuity, knowledge sharing and collaboration among team members (Kamar Mohamad et al., 2014). Potential disruptions in crane logistics and module transport can be reduced by circular modular approach, as involvement of new project members without the required skills can cause operational setbacks (Building and Construction Authority, 2017). Synergetic design and construction of circular MCPs can be stimulated through an integrated procurement system and contracting strategy Wuni et al. (2020b). Integrated approaches allow stakeholders to be included at all stages of the circular MCP lifecycle (Mohd Nawi et al., 2012).

Kyrö et al. (2019) found that to incorporate CE principles into design, construction and deconstruction of MCPs, specific guidelines, standards and policy endeavors need to be regulated and implemented. To get maximum benefits out of circular MCPs, design completion as early as possible is imperative (Choi et al., 2016). Because, modules can only be produced after building plans have been approved (L. Li et al., 2018). In their review, Wuni et al. (2020b) identified pertinent CSFs for circular MiC projects. These factors encompass comprehensive planning, appropriate design, efficient supply chain management, a capable factory inspection team, adequate site selection, seamless coordination of onsite and offsite work packages and effective inventory management.

Direct attention towards alternative, low-carbon activities that are related to Building Information Modeling and new technologies (i.e. 3D printing etc.) can help effectively integrate technological enablers under the structure of CE principles for prefabricated buildings (Zairul, 2021). Digital strategies i.e. BIM and material passports are recognized as facilitators of built environment integrated with CE principles. They play a crucial role in closing material loops and promoting sustainable resource management (Çetin et al., 2022).

Table 2.1 lists down the complete list of factors that can participate in the successful implementation of circular economy principles into modular construction activities.

Table 2.1: Preliminary List of factors influencing Circular MC

S/N	Contributing Factors	References
1	Dissemination of Circular Economy & Modular Construction	(Prendeville et al., 2018), (Wuni et al., 2020a), (Mignacca et al., 2020), (Hussein et al., 2021)
2	Skilled industry practitioners	(L. Li et al., 2018), (Wuni et al., 2020a)
3	Experienced Project Team	(L. Li et al., 2018), (Wuni et al., 2020b), (Wuni et al., 2022)

S/N	Contributing Factors	References
4	Earlier Engagement of Client	(Hwang et al., 2018), (El-Abidi et al., 2019), (Wuni et al., 2020b), (Hussein et al., 2021), (Wuni et al., 2022), (Charef, 2022),
5	Inclusion of Essential Stakeholders	(Wuni et al., 2020a), (Hussein et al., 2021), (Wuni et al., 2022)
6	Stakeholder Synergism	(Mohd Nawi et al., 2012), (Wuni et al., 2020a), (Wuni et al., 2023), (Hussein et al., 2021), (Wuni et al., 2022), (Charef, 2022)
7	Counsel with Specialty Contractor	(L. Li et al., 2018), (Nudurupati et al., 2022), (García et al., 2017)
8	Collaboration of Project Team	(Wuni et al., 2020b), (Hossain et al., 2020), (Norouzi et al., 2021), (Hussein et al., 2021), (Wuni et al., 2022)
9	Vigilant use of documentation management system	(Guerra et al., 2021), (Wuni et al., 2022)
10	Development of environmental policies (i.e., Govt. initiatives, public procurement, fiscal framework)	(Prendeville et al., 2018), (Wuni et al., 2020a), (Hossain et al., 2020), (Mignacca et al., 2020), (Castro et al., 2022), (Yu, Yazan, et al., 2022), (Yang et al., 2022), (Nudurupati et al., 2022), (Zairul, 2021), (Stephan et al., 2018)
11	Early involvement of certification body	(Kyrö et al., 2019), (Wuni et al., 2020a), (Wuni et al., 2022)
12	Proactive Planning for Circular MC	(El-Abidi et al., 2019), (Hussein et al., 2021), (Wuni et al., 2022)

S/N	Contributing Factors	References
13	Early Design Finalization	(Choi et al., 2016), (Kyrö et al., 2019), (Wuni et al., 2023), (Wuni et al., 2022)
14	Circular Design for Assembly	(Wuni et al., 2020b), (Joensuu et al., 2020), (Hossain et al., 2020), (Wuni et al., 2023), (Asif et al., 2021), (Hussein et al., 2021), (Iacovidou et al., 2021), (Guerra et al., 2021), (Castro et al., 2022), (Wuni et al., 2022), (Yang et al., 2022)
15	Design for Deconstruction	(Akanbi et al., 2018), (Akanbi et al., 2019), (Joensuu et al., 2020), (Mignacca et al., 2020), (Hossain et al., 2020), (Minunno et al., 2020), (Iacovidou et al., 2021), (Timothy et al., 2021), (Guerra et al., 2021), (Sanchez et al., 2021), (Yang et al., 2022)
16	Adoption of digital strategies (Artificial Intelligence, Digital twins, Digital marketplace etc.)	(Wuni et al., 2020a), (Iacovidou et al., 2021), (Nudurupati et al., 2022), (Yang et al., 2022), (Çetin et al., 2022)
17	Optimal use of Building Information Modelling	(Akanbi et al., 2018), (Hwang et al., 2018), (Ganiyu et al., 2020), (Sanchez et al., 2021), (Charef & Emmitt, 2021), (Zairul, 2021), (Wuni et al., 2022), (Yang et al., 2022), (Charef, 2022)
18	Additive manufacturing using recyclable materials	(Kromoser et al., 2022)

S/N	**Contributing Factors**	**References**
19	Circular use of Resources	(Mignacca et al., 2020), (Asif et al., 2021), (Machado et al., 2021), (Nudurupati et al., 2022)
20	Deliberation on critical tolerances among interfaces	(Mignacca et al., 2020), (Wuni et al., 2022)
21	Favourable site features and layout	(Wuni et al., 2022)
22	Integrated procurement system	(García et al., 2017), (El-Abidi et al., 2019), (Wuni et al., 2020a), (Wuni et al., 2022), (Yang et al., 2022)
23	Circular Supply Chain	(Leising et al., 2018), (El-Abidi et al., 2019), (Wuni et al., 2020a), (Hossain et al., 2020), (Mignacca et al., 2020), (Hussein et al., 2021), (Wuni et al., 2022), (Chen et al., 2022)
24	Inventory Optimization	(Hussein et al., 2021), (Nudurupati et al., 2022), (Wuni et al., 2022)
25	Adoption of just-in-time delivery mechanism	(Hussein et al., 2021), (Wuni et al., 2022)
26	Hedging strategies for delay evasion	(Hwang et al., 2018), (Nudurupati et al., 2022), (Wuni et al., 2022)
27	Offsite & Onsite Work Synchronization	(García et al., 2017), (Wuni et al., 2020a), (Wuni et al., 2023), (Wuni et al., 2022)
28	Time allowance for exclusive circular MC.	(Wuni et al., 2022)
29	Garnering data from project lifecycle	(Hossain et al., 2020), (Wuni et al., 2022)
30	Apt Structural System & Material	(Hossain et al., 2020), (Wuni et al., 2020a), (Mignacca et al., 2020), (Machado et al., 2021), (Iacovidou et

S/N	Contributing Factors	References
		al., 2021), (Nudurupati et al., 2022), (Wuni et al., 2022)

2.6 Complexity in Circular MC Adoption

The transition towards CE is crucial in the construction industry due to its substantial resource demands. Nevertheless, construction sector's distinctive industrial attributes and the complex nature of the Circular Economy itself obstruct the implementation of circular practices (Yu, Yazan, et al., 2022). The integration of CE practices within the built environment has progressed at a more sluggish rate when compared to other industries. There seems to be a noticeable absence of a comprehension of the systemic and multilevel dimensions of CE making it a complex matter to uptake, particularly concerning the factors that impede its practical implementation within the sector (Ababio et al., 2023). Therefore, a complex and complicated problem needs to be dealt with using an approach that acknowledges its complexity and proposes the most advantageous solution.

2.7 Systems Thinking Approach

To comprehend the origins and remedies of contemporary challenges, the conventional linear and mechanistic thought process must yield to a non-linear and organic perspective, often termed as systems thinking. This entails recognizing the significance of the entirety and prioritizing a holistic approach. Systems Thinking encompasses both the logic and creativity of connecting performance to structure and vice versa frequently with the aim of modifying the structure (relationships) to enhance overall performance (International Systems Dynamics Conference, 1994).

Systems thinking is a potent approach for comprehending and tackling complexity by centering on the entirety of a system, rather than isolating individual components. A specific facet of systems thinking is referred to as System Dynamics.

2.8 System Dynamics Approach

System dynamics is founded upon the fundamental principle of systems thinking, aimed at examining the dynamic intricacies and evolving patterns over time. It perceives a situation holistically and offers a structured approach to decipher the interconnectedness among components of a complex issue. SD can assist in the evaluation of strategies and offer insights into potential alterations within the system as schemas are put into action (Sterman, 2000). The SD approach entails the ability to construct "micro worlds" that render real-world challenges in a manner that is standard, pragmatic, structured, and simple to understand. SD confronts intricacy and develops links via a nonlinear feedback system. It can enhance the flow of information through collaborative technologies, hence leading to increased productivity (K. I. A. Khan et al., 2016).

Applying the systems-thinking approach necessitates creating a system dynamics model. SD techniques were employed in this study to create, simulate, calibrate, and validate potential factors that impact the integration of CE and MC, aimed at both economic considerations and environmental preservation. The process of model development involves multiple iterative stages:

- Recognition of components comprising systems (Orientors and indicators identification).
- Relationships and their interactions identification.

- Conceptual model formulation.
- Model implementation.
- Model calibration, verification, validation, and approval (Lektauers, 2015).

Employing a system dynamics approach holds promise in addressing these profoundly complex challenges. The multifaceted nature of integrating circular economy principles into modular construction practices is heavily influenced by the highly dynamic construction industry's norms within specific global regions. The inherent complexity poses a barrier to altering conventional practices. Consequently, a system dynamics approach will be adopted to effectively address and navigate these dynamics.

CHAPTER 3: RESEARCH METHODOLOGY

This research study examines the factors that influence the successful implementation of circularity in modular construction. The current chapter outlines the methodologies and procedures employed to attain the specific research objectives, delineated into five primary phases. The first stage being the preliminary study involves the review of literature for the identification of research gap, formulation a problem statement and consequently defining the research objectives. The second stage involves a systematic literature review that identifies contributing factors, followed by a conclusive content analysis. A preliminary questionnaire survey and factor analysis is also incorporated in this stage. Stage three begins with the conduction of a detailed questionnaire survey and evaluation thereby formulating an influence matrix, which will lead towards the formulation of causal loop diagram (CLD). In stage four, a system dynamics model was prepared, simulated and validated. Finally, stage five presents the results and outcomes of research along with the conclusion and discussion on future recommendations.

3.1 Precise Literature Review

A keen exploration of the research on modular construction and circular economy conducted in the last two decades helped finding a research gap, consequence objectives and identifying the factors contributing towards the adoption of CE principles into modular construction practices. As previously mentioned, there is limited research on the combined concept of modular construction and the circular economy. Therefore, articles focusing on critical success factors for modularity and circularity in construction individually are also considered.

After determining the research gap and defining the research objectives, a detailed scrutiny of literature published in reputed, peer-reviewed journals from 2015 onwards was carried out. The databases/registers i.e. Elsevier-Science Direct, Google Scholar, ResearchGate, Scopus and others were used to retrieve the relevant literature. Figure 3.1 presents the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram used for the systematic literature review conducted in this research study. Explicit keywords were used to get more productive and focused results, eliminating the articles not having them in title, abstract or keyword section. The exclusion criteria further included review articles, journal papers and conference papers and proceedings not directly related to the field of interest.

Hence, a total of 133 articles related to circular economy in construction and modular construction both individually as well as combined. The title and abstract screening reduced this number to 79. Which was further reduced in full-text screening to 42, leaving aside 37 articles not focusing on contributing factors for Circular MC. Afterwards, these 42 articles were reviewed to garner 30 most relevant factors listed in Table 2.1.

3.2 Content Analysis

Content analysis was conducted to assign literature scores to each identified factor based on their emphasis and frequency in the reviewed publications. Each of the factors was assigned a high, medium or low level of influence. Combining the ratings and frequencies, these factors were ranked based on the literature score (LS) calculated from relative importance index RII (Azman et al., 2019) using the equations (1) and (2). In Eq (1), W denotes the highest frequency, A represents the maximum possible score, and N is the number of papers considered in the systematic review. The normalized literature score in Eq (2) is calculated by dividing the LS of each factor by the sum of the LS of all factors.

$$\mathbf{RII = \frac{\Sigma W}{AxN}} \qquad \mathbf{(1)}$$

$$\mathbf{NLS = \frac{LS}{\Sigma LS}} \qquad \mathbf{(2)}$$

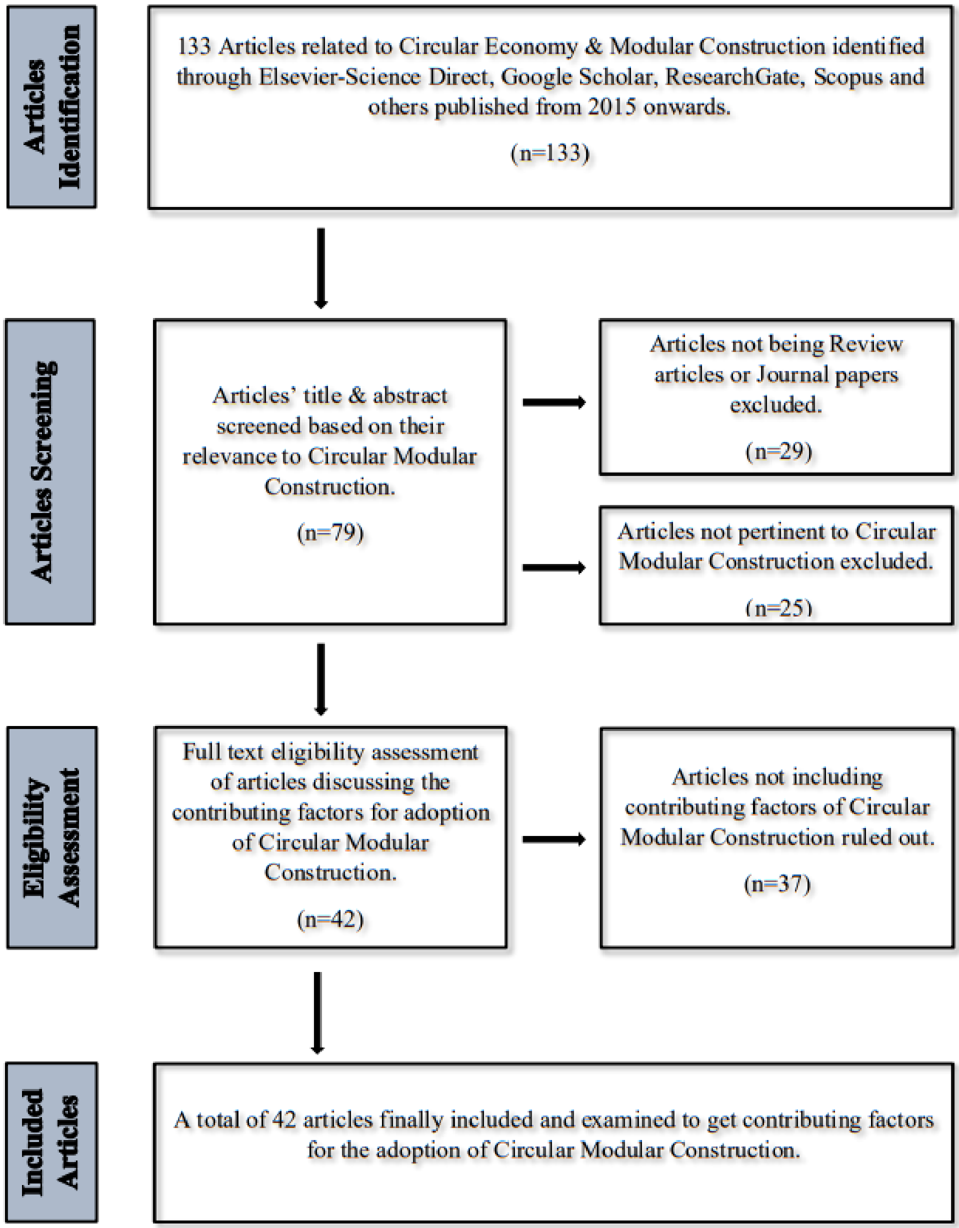


Figure 3.1: PRISMA Analysis Diagram

3.3 Preliminary Survey

A questionnaire survey was conducted preliminarily to shortlist the most significant factors based on the opinions of industry practitioners. The preliminary survey was administered on a small set of respondents i.e. 30, which is normally agreed upon by central limit theorem (Chan et al., 2018). Conducting these initial surveys allows us to rectify any issues with the construct items and address any observed misunderstandings among the respondents. This phase presents an opportunity for us to identify potential confusion regarding questionnaire items and gather suggestions from participants for potential enhancements. Undertaking a preliminary survey also provides a preliminary indication of the diversity of responses across different items, helping determine whether proceeding to a large-scale final survey is warranted. (Aithal, 2020).

The responses thus collected were analysed using statistical tests i.e. reliability and normality through SPSS®. Later, these factors were assigned field scores based on Eq (I) as RII forms the basis for factor ranking (Govindaraj et al., 2018). So, a final normalized score was obtained by combining the field normalized scores (FS) and literature normalized scores (LS) (Riaz et al., 2022). A weightage split ratio of 60 (FS)/40 (LS) (Riaz et al., 2022) was employed for ranking the factors. Whereas, to concentrate on factors having relatively greater significance, Pareto analysis of 80/20 rule as shown in Fig. 3 was used (Rashid et al., 2024) with 80% as cut-off point. It states that only 20% of the causes result in 80% of the outcomes (Karmaker et al., 2021) suggesting that the factors falling under 80% cut-off line are the vital-most affecting the fruitful implementation of circular MC. The weightage of respondent’s normalized score was kept higher to incorporate the pulse of construction industry of the day. Hence, the preliminary analysis brought forward 20 top rated factors through which the integration of CE strategies in the prefabrication cum modular construction practices could be positively impacted.

3.4 Detailed Survey

Considering these 20 shortlisted factors influencing the extensive uptake of circular MC as a preamble, a detailed questionnaire was developed to further explore their potential to contribute along with their inter-relationships, functionalities and co-dependencies. A total of 380 relationships were made part of this questionnaire which were to be assessed for their level of influence and relative polarities.

3.5 Optimum Sample Size

The optimal number of respondents for detailed questionnaire survey was determined to be 121 (Riaz et al., 2022) using Slovin's formula shown in Eq (3) (Ephantus E et al., 2015).

$$n = \frac{N}{1 + Ne^2} \tag{3}$$

Here, N is the population size, n is the number of respondents and e is error margin i.e. the desirable precision of 0.05 for a 95% level of confidence.

3.6 Check for Consistency and Reliability

The reliability and internal consistency of the obtained data were examined through the Cronbach's Alpha test. A threshold value of 0.7 for Cronbach's Alpha indicates that the data is reliable and internally consistent (Taber, 2018). A value as high as 0.9 suggests a highly reliable and internally consistent data.

3.7 Influence Matrix

A The influence matrix considering the most momentous factor relationships was developed having 21 significant relations. Identification of these critical interrelations was done based on the mean value of influence level e.g. low, medium or high using Eq (4). The questionnaire's questions not being discrete and stand-alone in nature necessitated the use of mean value rather than the mode value (Jr et al., 2012).

$$\text{Mean Value} = \frac{1 \times \text{Low} + 3 \times \text{Medium} + 5 \times \text{High}}{\text{Number of respondents}} \qquad (4)$$

The mean value was further used to get RII value. The direct or indirect polarity of the relationships was also established.

3.8 System Dynamics Approach and SD Model

The influence matrix set the foundation for preparation of causal loop diagram depicting all the significant interrelationships. The CLD thus produced clearly portrayed the crucial relations and their polarity. The produced CLD was checked by experts to make sure it made sense and was applicable to the construction sector. The results formed several significant and pertinent loops. This led to the formation of a stock and flow diagram whereby introducing an extra stock to track the convergence of current stocks. Then the RII values of each relationship were incorporated into the model to form a thorough System Dynamics Model that was simulated explicitly over a span of five years

3.9 Model Validation

The SDM developed in this research was intended to counter the intricacy involved in the uptake of circular modular construction practices in existing trends of industry. Therefore, it is elementary to validate the model (Riaz et al., 2022). For this purpose, five conclusive tests were carried out , which includes structure verification, boundary adequacy test, extreme condition & parameter verification, (Qudrat-Ullah et al., 2010) along with sensitivity analysis (Hekimoglu et al., 2010).

3.10 Summary

This chapter provides a comprehensive description of the methodology employed in this study. The steps involved in each of the four stages including literature retrieval, content analysis, preliminary and detailed surveys, system dynamics approach to model verification were discussed in detail. The next chapter will present the results and outcomes of data analysis.

CHAPTER 4:RESULTS AND DISCUSSIONS

The current chapter discusses the results obtained at each step of research as detailed previously for the achievement of research objectives. To rank and shortlist out of 30 recognized contributing factors for circular modular construction, a content analysis and preliminary survey was conducted. Then a detailed questionnaire based on the top ranked factors was circulated among industry professionals working in developing economies around the world. Analysis of the responses brought forward 21 significant interrelationships among these factors which helped produce causal loop diagrams and ultimately the system dynamics model. Expert opinion and model validation tests were employed to finalize the model for adoption.

4.1 Preliminary Survey and Analysis

A rigorous and precise exploration of literature based on 42 most relevant research papers and articles brought forward a total of 30 explicit factors that could benefit the shift from linear approach to circular in modular realm of construction. According to the stress laid on each factor, a literature normalized score was calculated using RII (Eq 1).

Subsequently, a questionnaire was designed to ask the respondents to rate each factor on Likert scale from 1 to 5, where 1 indicates very low and 5 indicates very high based on their level of contribution to the said objectives. The questionnaire consisted of two sections: the first part gathered information about the personnel, while the second part focused on assessing the factors. Following Tahir et al. (2021)’s footsteps, a sample size of 30 was used and the respondents were accessed through social connectivity websites i.e. LinkedIn (Abbas et al., 2019) based on their organizational profiles. Google forms was used to conduct preliminary survey and circulated in the target audience, 75% of whom belonged to the field of construction management. The rest had been working in other fields of civil engineering i.e. architecture, structure design, site execution etc. 18.8% of the respondents were clients, 25% were consultants, and 40.6% were contractors.

Respondent’s analysis indicated that 42.6% had bachelor’s as the highest level of qualification. 46.7% had master’s degrees and 10.7% had PhDs in the relevant field. 58.2% respondents had relevant field experience of 2 to 5 years, 16.7% and 13.3% had 6 to 10 and 11 to 15 years’ experience respectively. Only 11.8% respondents being fresh graduates. To carry out the research in developing countries (Jahan et al., 2022), around 18 out of 30 responses were obtained from developing countries other than Pakistan and only 12 out of 30 from the construction professionals working within Pakistan. The countries abroad included Hungary, India, China, Bangladesh, Tanzania, Qatar, Saudi Arabia and Oman.

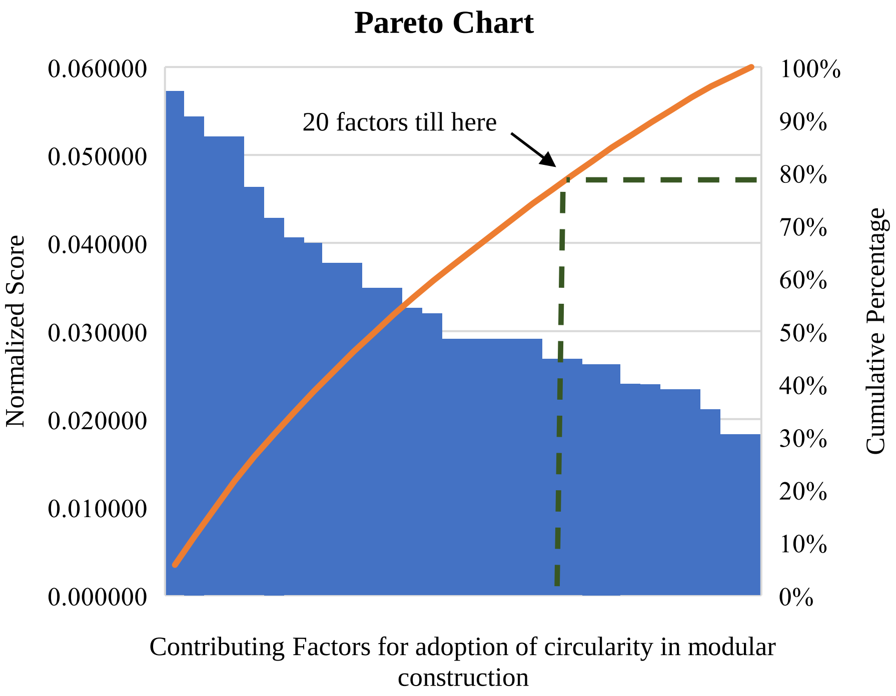


Figure 4.1: Cumulative Frequency Chart

Analyzing the responses, a field normalized score was calculated for each factor. Both field and literature normalized scores combined in the ratio of 60/40 formed the ground for ranking all the 30 factors. 20 factors in total were shortlisted based on over 80% cumulative combined significance to include the greatest possible influence as shown in Figure 4.1. A comparison of literature normalized score, field normalized score for each of the shortlisted factors along with their combined significance of 60/40 and cumulative normalized score is listed in Table 4.1.

Table 4.1 Top Ranked Shortlisted Factors

Ran-king	Shortlisted Factors - Circular Modular Construction	Normalized Field Score	Normalized Literature Score	Total Score (60/40)	Cumulative Normalized Score
1st	Design for Deconstruction	0.042735	0.079023	0.05725	0.05725
2nd	Development of environmental policies	0.034188	0.079023	0.05438	0.11163
3rd	Circular Design for Assembly	0.034188	0.079023	0.05212	0.16375
4th	Optimal use of Building Information Modelling	0.042735	0.071839	0.05212	0.21587
5th	Circular Supply Chain	0.034188	0.064655	0.04637	0.26225
6th	Stakeholder Synergism	0.042735	0.043103	0.04288	0.30513
7th	Apt Structural System & Material	0.034188	0.050287	0.04063	0.34576
8th	Integrated procurement system	0.042735	0.035920	0.04001	0.38576
9th	Collaboration of Project Team	0.034188	0.043103	0.03775	0.42352
10th	Dissemination of Circular Economy & Modular Construction	0.034188	0.035920	0.03775	0.46127

Ran-king	**Shortlisted Factors - Circular Modular Construction**	**Normalized Field Score**	**Normalized Literature Score**	**Total Score (60/40)**	**Cumulative Normalized Score**
11th	Adoption of digital strategies	0.034188	0.043103	0.03488	0.49615
12th	Circular use of Resources	0.034188	0.035920	0.03488	0.53103
13th	Early Design Finalization	0.034188	0.028736	0.03263	0.56366
14th	Earlier Engagement of Client	0.025641	0.043103	0.03201	0.59567
15th	Counsel with Specialty Contractor	0.034188	0.021552	0.02913	0.62480
16th	Inclusion of Essential Stakeholders	0.034188	0.021552	0.02913	0.65393
17th	Experienced Project Team	0.034188	0.021552	0.02913	0.68307
18th	Proactive Planning for Circular MC	0.034188	0.021552	0.02913	0.71220
19th	Inventory Optimization	0.025641	0.028736	0.02913	0.74134
20th	Offsite & Onsite Work Synchronization	0.025641	0.028736	0.02688	0.76821

4.2 Detailed Survey and Analysis

The third stage of the research study started off with a detailed survey. For this purpose, a comprehensive questionnaire was formulated having two sections in general. The first part enquires about the personal and professional information e.g. academic qualification, years and country of professional experience, field of work and organization type. The second part draws a comparison of one factor with the rest of the 19 other factors to establish the influence and polarity of the relation. The influence is to be rated on the Likert scale as 1 through 5 where 1 reflects low, 3 medium and 5 reflects high. Polarity can be chosen as direct or indirect. When an increase in one variable results in an increase in another variable, this is known as a direct relationship. However, if increase in one decreases the other, then it is termed as indirect relation. In a similar manner, all 20 of the factors were analyzed one at a time making it a total of 380 relationships, out of which only the most significant 21 were selected.

Google Forms® was used to draft the questionnaire in a grid format. Sample size was calculated using Eq III and the optimal sample size came out to be 121 (Riaz et al., 2022). Therefore, the questionnaire was forwarded to more than 180 industry professionals. In total, 177 responses were collected. Of these, 56 were found to be invalid, leaving 121 valid responses for further analysis. Respondents were accessed through their social media accounts on LinkedIn®, Facebook®, WhatsApp® and official emails on Gmail® and Outlook®. Since the study focused on finding a framework for adoption of CE integrated modular construction in developing economies around the world. Hence, the experts working in developing counties i.e. India, Saudi Arabia, South Africa, China, Iran, Oman, Egypt, Türkiye, Hungary, Ethiopia, Tanzania, Sri Lanka, Afghanistan, Indonesia, Bangladesh, Qatar and Brazil were approached. The developing nations with lesser research on circular modular construction were chosen (World Economic Forum, 2018). The distribution of the respondents' responses was dispersed as shown in Figure 4.2, which is a typical occurrence in the places where data is collected. Identical schema was observed in other researches i.e. (Ghufran et al., 2022; Jahan et al., 2022). Reasons such as a limited exposure to circular modular construction and assorted levels of awareness and interest regarding the topic may have contributed to this outcome (Amin et al., 2022). Nonetheless, the effect of this non-uniformity was catered through a keen analysis of data and its correspondence to the culture and field practices. It was further rectified by model validation by means of field experts.

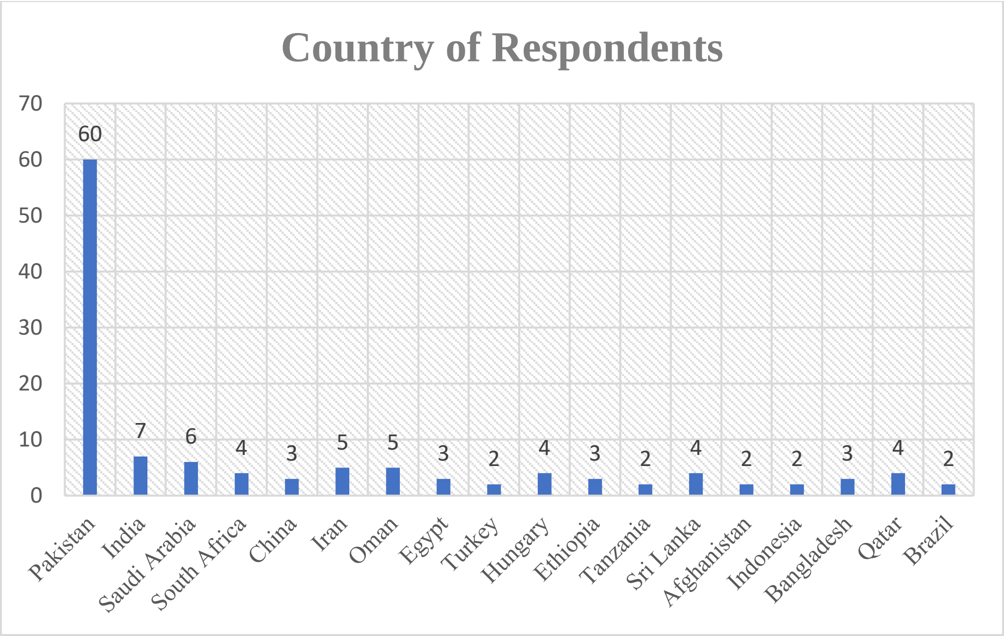


Figure 4.2: Respondents’ Country of Response

In context of organization type, a major chunk of respondents was affiliated with consultants (28%) and contractors (29%). 31% worked with clients, 10% were a part of academic institutions and only 2% were working with subcontractors. Figure 4.3 shows organization type distribution on a pie chart. Table 4.2 shows rest of the demographic detail regarding the respondents. The data indicated that 40% of the respondents held a bachelor's degree, 49% had a master's degree, and 11% had a PhD as their highest level of qualification. As far as working experience is concerned, 35% of respondents had been working for 1 to 5 years, 36% for 6 to 10 years, 12% for 11 to 15 years, 12% had been in the relevant industry for 16 to 20 years and 6% for a period of more than 21 years. Construction management was the field of 31% of the respondents, 22% were involved in project execution at site, 26% in building design, 10% in engineering academics, 4% worked as quantity estimators, 2% as architects and remaining 5% mentioned their specific field of work e.g. urban planning, contract management, oil & gas development etc.

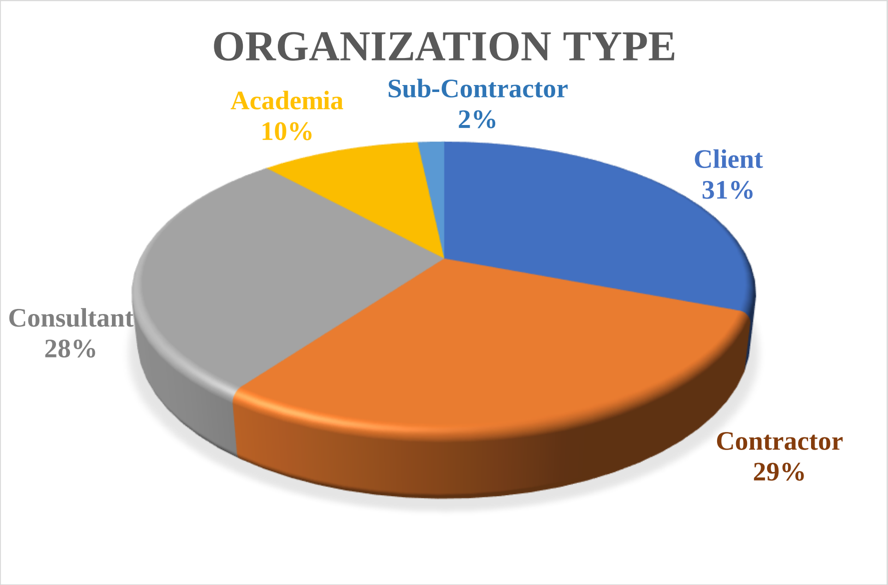


Figure 4.3: Respondents’ Organization Type

Table 4.2: Respondents' Demographics and Response Frequency

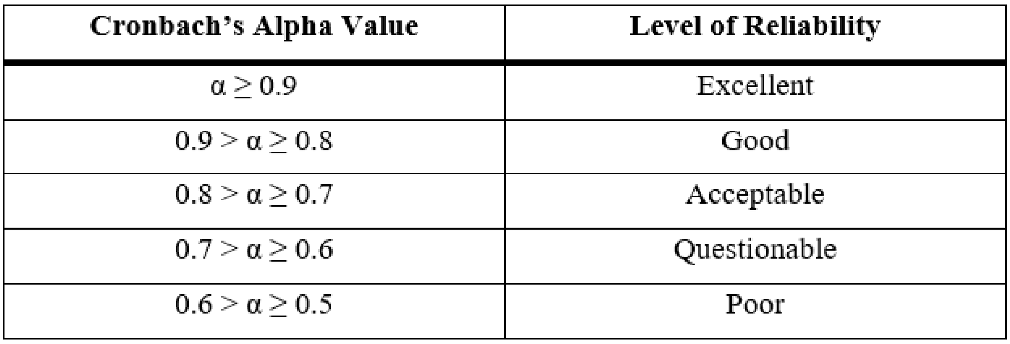
Type	Profile	Frequency	Percentage
Academic Qualification	Bachelors (BS/B.Sc.)	49	40%
	Masters (MS/M.Sc.)	59	49%
	Doctorate (PhD/D.Eng.)	13	11%
Professional Experience (Years)	1 to 5	42	35%
	6 to 10	43	36%
	11 to 15	14	12%
	16 to 20	15	12%
	21 and above	7	6%
Field of Work	Construction Management	37	31%
	Building Design	32	26%
	Project Execution at Site	27	22%
	Engineering Academics	12	10%
	Quantity surveying	5	4%
	Architectural	2	2%
	Others	6	5%

During the data filtering, some of the responses had to be dropped out because of various reasons such as missing values, data duplicates, format errors etc. Respondents having practical experience of less than one year were also not considered for further analysis. All these anomalies were addressed to retain a reliable and consistent stream of responses

4.3 Detailed Analysis

The reliability and internal consistency of the responses were evaluated using SPSS® version 29. Table 4.3 presents the threshold values for Cronbach's Alpha regarding internal consistency, while Table 4.4 displays the Cronbach's Alpha value for the data collected from the detailed survey. The α value of 0.9 shows that the data is internally consistent and reliable

Table 4.3: Cronbach's α Threshold Values-The Relationship among Cronbach's α & Data Reliability



Cronbach's Alpha Value	Level of Reliability
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor

Table 4.4: Reliability Statistics

Cronbach's Alpha	Number of Items
0.9	380

After the culmination of 20 top ranked factors that are pivotal to the endorsement of circular MC, the next essential step was to comprehend the dependencies of each factor with the remaining 19 factors. Hence, the core purpose of this survey was to identify the nature of relationships being direct or inverse and the reciprocal influence of these factors (Akhtar et al., 2024; Ghufran et al., 2022). The analysis of responses signified twenty-one (21) causal relations among these factors as depicted in Table 4.5. The impacting and impacted factors along with their respective mean value, relative importance index and polarity have been reported. Relationships having mean values, calculated using Eq (4), greater than 4 and less than 5 were taken for further assessment (Chong et al., 2017). Examining these interactions of the contributing factors, a multi-faceted strategy can be devised for turning the linear modular construction approach towards a circular one.

Table 4.5: Impacted & Impacting Factor Relationships

Sr. No	Impacting Factors	Impacted Factors	Mean	RII	Polarity
1	Experienced Project Team	Dissemination of CE & MC	4.17	0.83	Direct
2	Inclusion of Essential Stakeholders	Experienced Project Team	4.16	0.83	Direct
3	Design for Deconstruction	Experienced Project Team	4.06	0.81	Direct
4	Inclusion of Essential Stakeholders	Earlier Engagement of Client	4.69	0.94	Direct

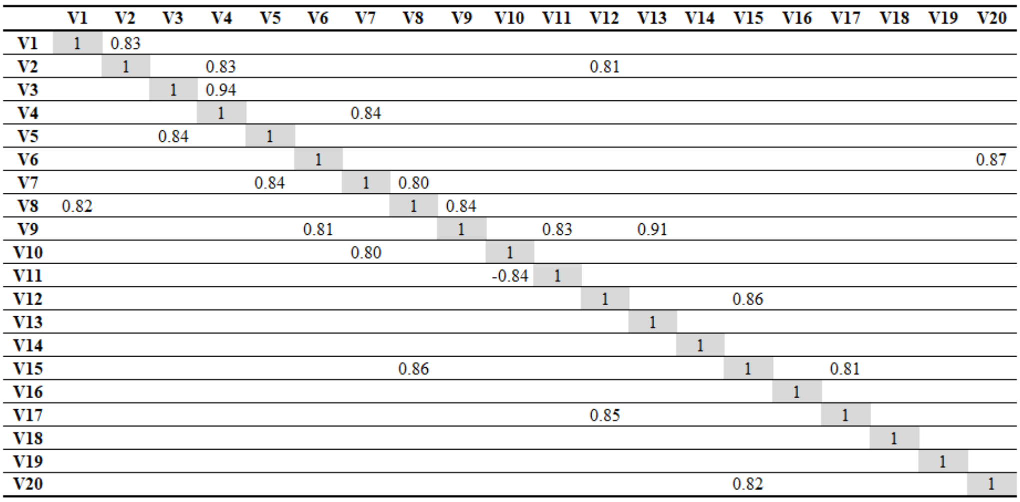
Sr. No	Impacting Factors	Impacted Factors	Mean	RII	Polarity
5	Collaboration of Project Team	Inclusion of Essential Stakeholders	4.21	0.84	Direct
6	Earlier Engagement of Client	Stakeholder Synergism	4.22	0.84	Direct
7	Apt Structural System & Material	Counsel with Specialty Contractor	4.36	0.87	Direct
8	Stakeholder Synergism	Collaboration of Project Team	4.21	0.84	Direct
9	Development of Environmental Policies	Collaboration of Project Team	4.02	0.80	Direct
10	Dissemination of CE & MC	Development of Environmental Policies	4.12	0.82	Direct
11	Proactive Planning for Circular MC	Development of Environmental Policies	4.22	0.84	Direct
12	Counsel with Specialty Contractor	Proactive Planning for Circular MC	4.06	0.81	Direct
13	Circular Design for Assembly	Proactive Planning for Circular MC	4.14	0.83	Direct
14	Adoption of Digital Strategies	Proactive Planning for Circular MC	4.57	0.91	Direct
15	Collaboration of Project Team	Early Design Completion	4.01	0.80	Direct
16	Early Design Completion	Circular Design for Assembly	4.19	-0.84	Indirect
17	Circular use of Resources	Design for Deconstruction	4.31	0.86	Direct

Sr. No	Impacting Factors	Impacted Factors	Mean	RII	Polarity
18	Development of Environmental Policies	Circular use of Resources	4.29	0.86	Direct
19	Circular Supply Chain	Circular use of Resources	4.07	0.81	Direct
20	Design for Deconstruction	Circular Supply Chain	4.26	0.85	Direct
21	Circular use of Resources	Apt Structural System & Material	4.09	0.82	Direct

4.4 Polarity Matrix

The relationships and their associated polarities, significant enough to help promote the uptake of modular construction with integrated circularity, were validated through expert opinion. They were then represented in a form of matrix explicitly portraying the relationships and polarity. Table 4.6 sheds light on it by presenting impacting factors on x-axis while the impacted factors on y-axis. A positive sign means direct relation whereas, negative sign shows an indirect/inverse relation. Of a total 21 prequalified relationships, 20 were direct and only 1 turned out to be inverse.

Table 4.6: Influence Matrix



	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20
V1	1	0.83																		
V2		1		0.83								0.81								
V3			1	0.94																
V4				1			0.84													
V5			0.84		1															
V6						1														0.87
V7					0.84		1	0.80												
V8	0.82							1	0.84											
V9						0.81			1		0.83		0.91							
V10							0.80			1										
V11										-0.84	1									
V12												1			0.86					
V13													1							
V14														1						
V15								0.86							1		0.81			
V16																1				
V17												0.85					1			
V18																		1		
V19																			1	
V20															0.82					1

Here, V1: Dissemination of CE & MC, V2: Experienced Project Team, V3: Earlier Engagement of Client, V4: Inclusion of Essential Stakeholders, V5: Stakeholder Synergism, V6: Counsel with Specialty Contractor, V7: Collaboration of Project Team, V8: Development of Environmental Policies, V9: Proactive Planning for Circular MC, V10: Early Design Completion, V11: Circular Design for Assembly, V12: Design for Deconstruction, V13: Adoption of Digital Strategies, V14: Optimal use of BIM, V15: Circular use of Resources, V16: Integrated Procurement System, V17: Circular Supply Chain, V18: Inventory Optimization, V19: Offsite & Onsite Work Synchronization, V20: Apt Structural System & Material, X-Axis: Impacting Factors, Y-Axis: Impacted Factors.

The influence matrix reads; factor V1 is positively influenced by factor V2 with an RII value of 0.83, V2 is influenced by V4 and V12 having 0.83 and 0.81 as RII values respectively. Both and positively impacting V2 where V4 has higher impact. Similarly, V11 is inversely influenced by V10 with an intensity of -0.84. Hence, this influence matrix (IM) was later used to develop CLD and SDM.

4.5 Casual Loop Diagram

Following the footsteps of Bertassini et al. (2021), relationships as depicted in the influence matrix were used to develop various pertinent causal loops through Vensim PLE® software. The logic and expressiveness of loops was ensured by experts' input. Two types of causal loops were encountered, one being reinforcing and the other being the balancing loop. Reinforcing loops depict self-reinforcing mechanisms within a system, where a change in one variable exerts a cumulative effect on the entire system. This can lead to a system exhibiting continual improvement or reduction, highlighting the significance of beginning circumstances. In contrast, balancing loops create counteracting forces in response to changes in one variable, which help restore the system to its optimal state, thereby promoting stability. The balancing loops exhibit how a system sustains equilibrium or adjusts to disruptions thereby being capable of self-regulation and stabilization. By and large, these loops function similarly to Newton's third law, which states that every action has an equal but opposite response. This keeps the entire system in balance (Akhtar et al., 2024). A total of 6 loops were identified in the CLD as shown in Figure 4.4, out of which 5 were reinforcing and 1 was balancing. Each of these loops are explained as follows.

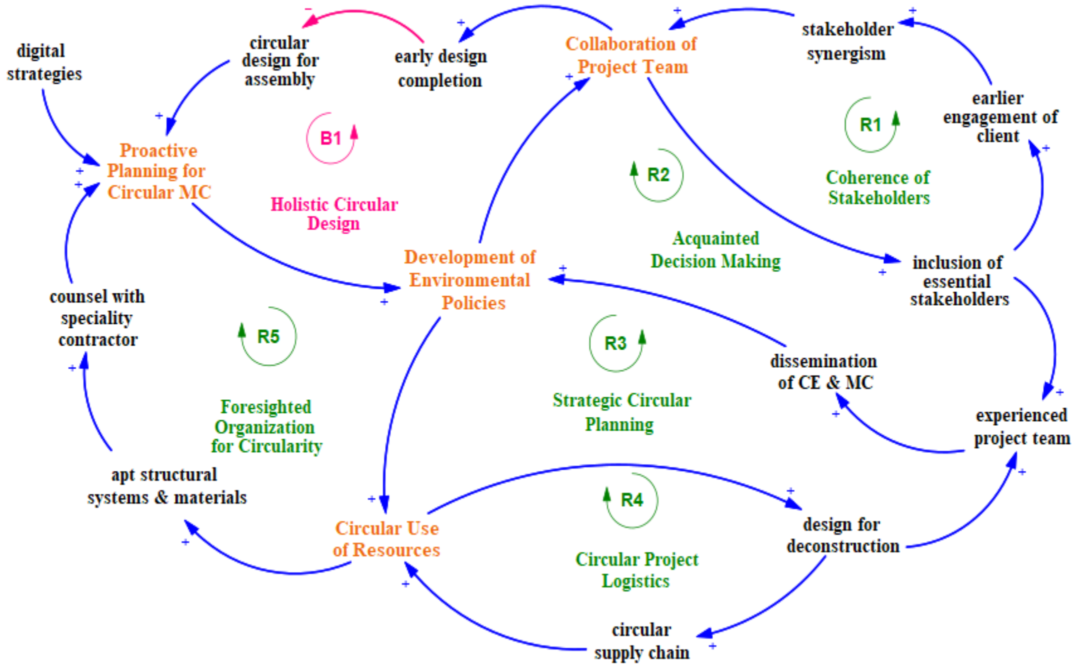


Figure 4.4: Causal Loop Diagram (CLD)

4.5.1 R1-Reinforcing Loop (Coherence of Stakeholders)

R1 is the reinforcing loop that signifies the coherence and cooperation of key stakeholders as shown in Figure 4.5. It indicates that the more essential stakeholders are included, the greater the client's engagement will be at earlier stages. Whereas the early and active involvement of the client will encourage all stakeholders to work in an integrated environment to get the best possible outputs. This will ultimately lead towards the increased collaboration and interaction of the whole project team. Therefore, this loop establishes that collaborative techniques foster stakeholder integration (Mohd Nawi et al., 2012) for the conception of circular approach in traditional modular construction practices.

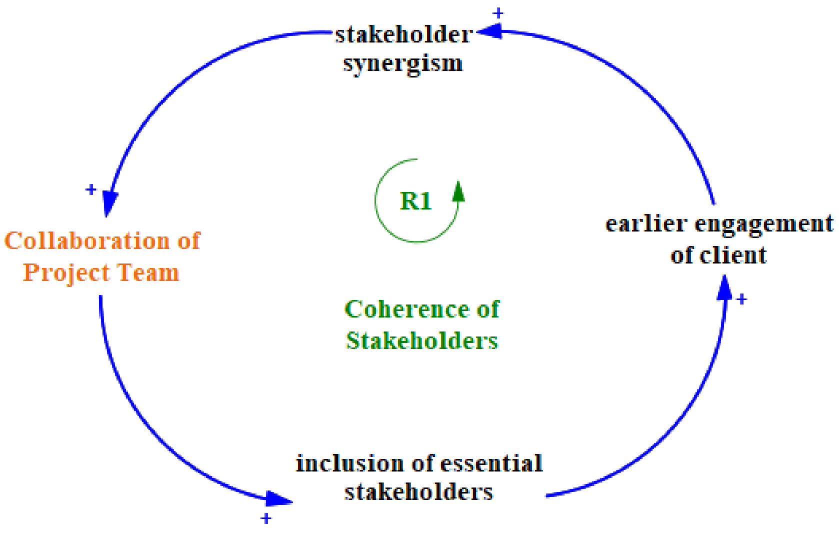


Figure 4.5: R1-Reinforcing Loop

4.5.2 R2-Reinforcing Loop (Acquainted Decision Making)

The second loop R2 has a reinforcing effect and revolves around the benefactors of a well-informed, knowledgeable and acquainted decision-making process in circular modular construction. Figure 4.6 shows how wide spread of awareness and understanding of CE and its positive influence on prefabrication industry can inspire the policy makers to formulate framework of regulations for its uptake. These policy incentives and limitations can promote the collaboration of proficient project teams to work in conjoint manner ensuring the participation of critical project stakeholders. Consequently, creating collaboration mechanism for material circularity throughout its life and fostering cooperation among various participants through effective stakeholder management could significantly enhance the promotion of CE (Geissdoerfer et al., 2018).

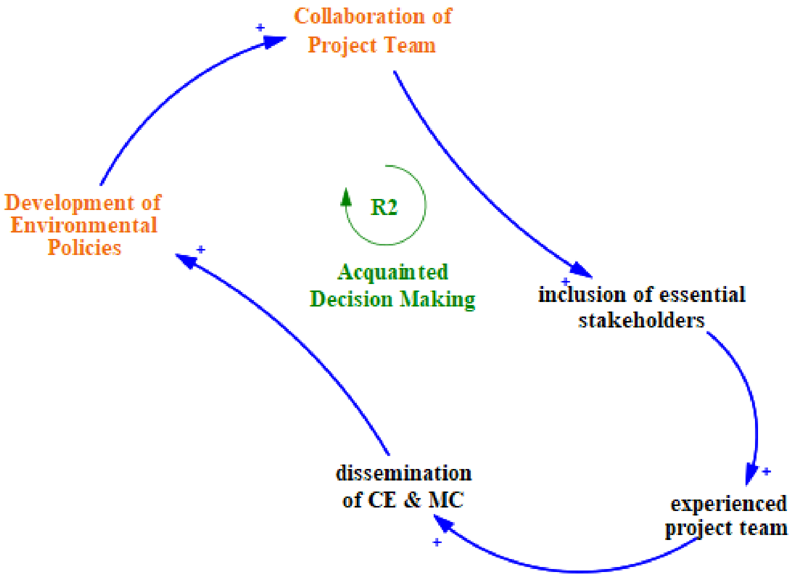


Figure 4.6: R2-Reinforcing Loop

4.5.3 R3-Reinforcing Loop (Strategic Circular Planning)

The third reinforcing loop R3 strengthens the need of extensive strategic planning to instigate circularity in the prevailing take-make-dispose approach. Just as summarized by Kyrö et al. (2019), the loop R3 as shown in Figure 4.7 depicts the importance of effective dedicated rules, regulations, and legislative actions necessary to control the design, execution and dismantling operations of modular construction integrated with CE principles. An experienced and proficient team can contribute to the dissemination of knowledge leading to the establishment of certain policies enforcing the circular use of resources based on a proactive design for deconstruction.

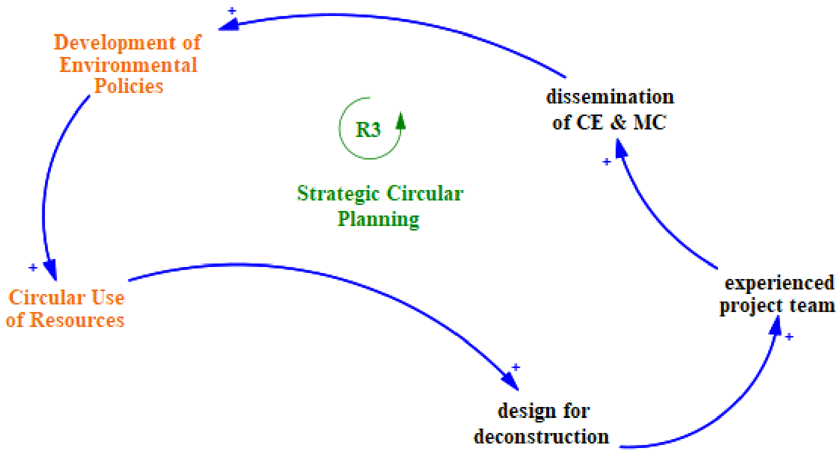


Figure 4.7: R3-Reinforcing Loop

4.5.4 R4-Reinforcing Loop (Circular Project Logistics)

The loop R4 is relatively simpler one having a reinforcing effect on the system. It shows that material resources can have extended life by narrowing down the recourse loop i.e. reducing consumption, increasing reuse, and enhancing recycling practices. This can promote the idea of design for disassembly/deconstruction which can be achieved by multiple tools i.e. BIM based design, and techniques i.e. Life Cycle Assessment (LCA). Furthermore, it can be seen in the Figure 4.8 that the project supply chain must employ a circular approach to realize its benefits in the longer run. Best way of turning conventional to a circular supply chain is to incorporate strategic CE practices in every phase of supply chain (Chen et al., 2022), be it the planning, procurement, fabrication, logistics, assembling, O&M or end-of-life phase.

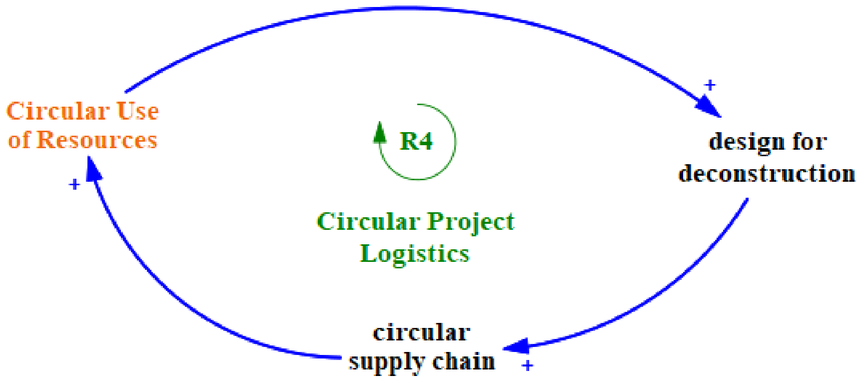


Figure 4.8: R4-Reinforcing Loop

4.5.5 R5-Reinforcing Loop (Foresighted Organization for Circularity)

The reinforcing loop R5 is a combination of multiple factors, which when combined, form the basis for a farsighted organization and planning for circularity. Fig. 11 shows how a regulated set of policies entrusted by authorities can increase the focus on the use of appropriate materials and structural systems for circular use. For maximum possible valuable outcomes, it is imperative to seek the guidance, support and expertise of manufacturers and specialty contractors (L. Li et al., 2018). The input thus received will help enhance the quality of circular MC planning. In addition to that, digital tools and strategies are considered as facilitators of proactive circular planning (Çetin et al., 2022). Most prominent of these strategies are artificial intelligence, digital twins, BIM, material passports and digital marketplaces accompanying scanning techniques.

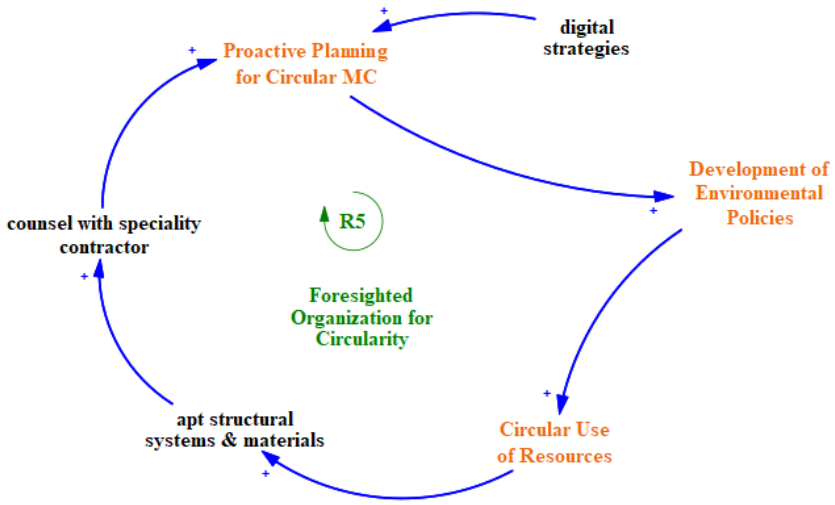


Figure 4.9: R5-Reinforcing Loop

4.5.6 B1-Balancing Loop (Holistic Circular Design)

The balancing loop B1 emphasizes the need of a holistic overarching circular design for modular construction projects. Fig. 12 indicates how design with an intension of manufacturing and assembly is critical in advance of large scale and high-stake factory manufacturing. However, earlier design completion and finalization is also imperative (Wuni et al., 2023). As the production phase cannot begin unless the entire detailed design has been completed and approved by relevant forum (L. Li et al., 2018). A slight change in design or specifications can disrupt the prefabrication process and will lead to loss of resources and capital (Wuni et al., 2020b). Therefore, a collaborative effort of well experienced team members along with bespoke regulations set by approving authorities can help finalize the design as early as possible.

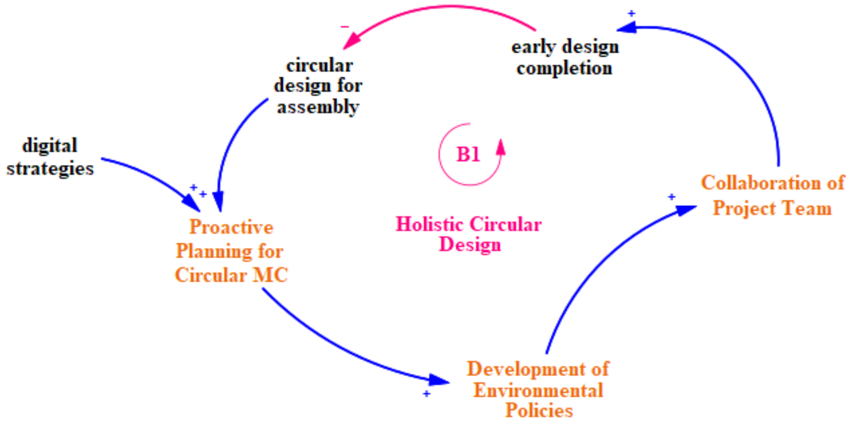


Figure 4.10: B1-Balancing Loop

4.6 Feedback Loop Analysis

A thorough analysis of the developed causal loop diagram based on the magnitude of strength, nature and speed of feedback loops was conducted. The results are listed in the Table 4.7 shown below. A total of six loops were identified out of which five were reinforcing in nature of polarity and one was balancing. Loops R1, R2, R3, R4 and R5 were having a reinforcing effect on the system with stronger impact and higher speed. This implies that these critical loops have a great tendency to achieve the goal in relatively lesser time frame. On the contrary, loop B1 was impacting strongly but at a slower speed along with an overall balancing effect indicating that the factors thus involved will have a considerable impact but at gradual pace.

Table 4.7: Impacted & Impacting Factor Relationships

Loop	Nature of Influence	Speed of Influence	Strength of Influence
R1	Reinforcing	Fast	Strong

Loop	Nature of Influence	Speed of Influence	Strength of Influence
R2	Reinforcing	Fast	Strong
R3	Reinforcing	Fast	Strong
R4	Reinforcing	Fast	Strong
R5	Reinforcing	Fast	Strong
B1	Reinforcing	Slow	Strong

This type of analysis helps focusing on the factors having the most immediate impact on the system. Any slight change in any of the factors associated with these loops will increase the impact of the rest of factors manifolds. The functionality of these loops was validated with the help of field experts having experiences more than a decade. Their practical acumen strengthened the accuracy of CLD consequently establishing a strong foundation for the model.

4.7 System Dynamics Model

Modular A system dynamics model was formulated using Vensim PLE® software version V29 as depicted in Figure 4.11 based on the CLD developed. The RII value as listed in Table 4.5 was calculated using the mean values derived from the mutual influence of 20 shortlisted factors. 21 noteworthy factor interrelations; 20 being directly related while 1 being indirect, were established. The same set of information had also been tabulated in the form of an influence matrix. Four stocks namely, Development of Environmental Policies, Circular Use of Resources, Collaboration of Project Team and Proactive planning for Circular MC, were introduced into the system. All these factors were made into stocks as they had the highest number of interrelations and were demonstrating cumulation of other factors in the CLD. They all had their respective inflows and outflows. A new stock i.e. Adoption of Circularity in Modular Construction was introduced by converging the outflows of all four stocks to represent the cumulative effect of the system.

The equations of inflows and outflows of each stock are presented in Eq (5) to (14).

$$\text{Policy Inflow} = 0.047 \times V1 + 0.048 \times V9 + 1 \times V8$$

$$\text{Strategic Outflow} = 1 \times V8$$

$$\text{Resource Inflow} = 0.049 \times V8 + 0.046 \times V17 + 1 \times V15$$

$$\text{Resource Outflow} = 1 \times V15$$

$$\text{Collaborative Inflow} = 0.048 \times V5 + 0.046 \times V8 + 1 \times V7$$

$$\text{Productive Outflow} = 1 \times V7$$

$$\text{Planning Inflow} = 0.046 \times V6 + 0.047 \times V11 + 0.052 \times V13 + 1 \times V9$$

$$\text{Planning Outflow} = 1 \times V9$$

$$\text{CMC Inflow} = V8 + V15 + V7 + V9 + 1 \times \text{Adoption of Circular MC}$$

$$\text{CMC Outflow} = 1 \times \text{Adoption of Circular MC}$$

Where V1 stands for Dissemination of CE & MC, V5 stands for Stakeholder Synergism, V6 stands for Counsel with Specialty Contractor, V7 stands for Collaboration of Project Team, V8 stands for Development of Environmental Policies, V9 represents Proactive Planning for Circular MC, V11 represents

Circular Design for Assembly, V13 represents Adoption of Digital Strategies, V15 represents Circular use of Resources and V17 represents Circular Supply Chain.

4.8 Simulation and Discussion

The system dynamics model was developed in context with the contributing factors to envision their anticipated behavior over time. For which, each of the stocks was simulated for a five years period (Riaz et al., 2022) using VENSIM software. Besides an added stock was introduced and simulated for a span of five years to foresee the augmented outcome of all four stocks converging on it. The five-year timeframe was chosen to ensure that the execution is optimal and effective. Additionally, the implementation of CE principles in the construction sector in general has garnered considerable attention within the last decade. But its exclusive implementation in modular construction is relatively novel especially to the developing countries. Fig. 14 shows the graphical representation of the result of stock simulations. Time propagation in years is plotted on x-axis while the y-axis indicates normalized relative importance index values inferring the intensities of stocks and factors under consideration.

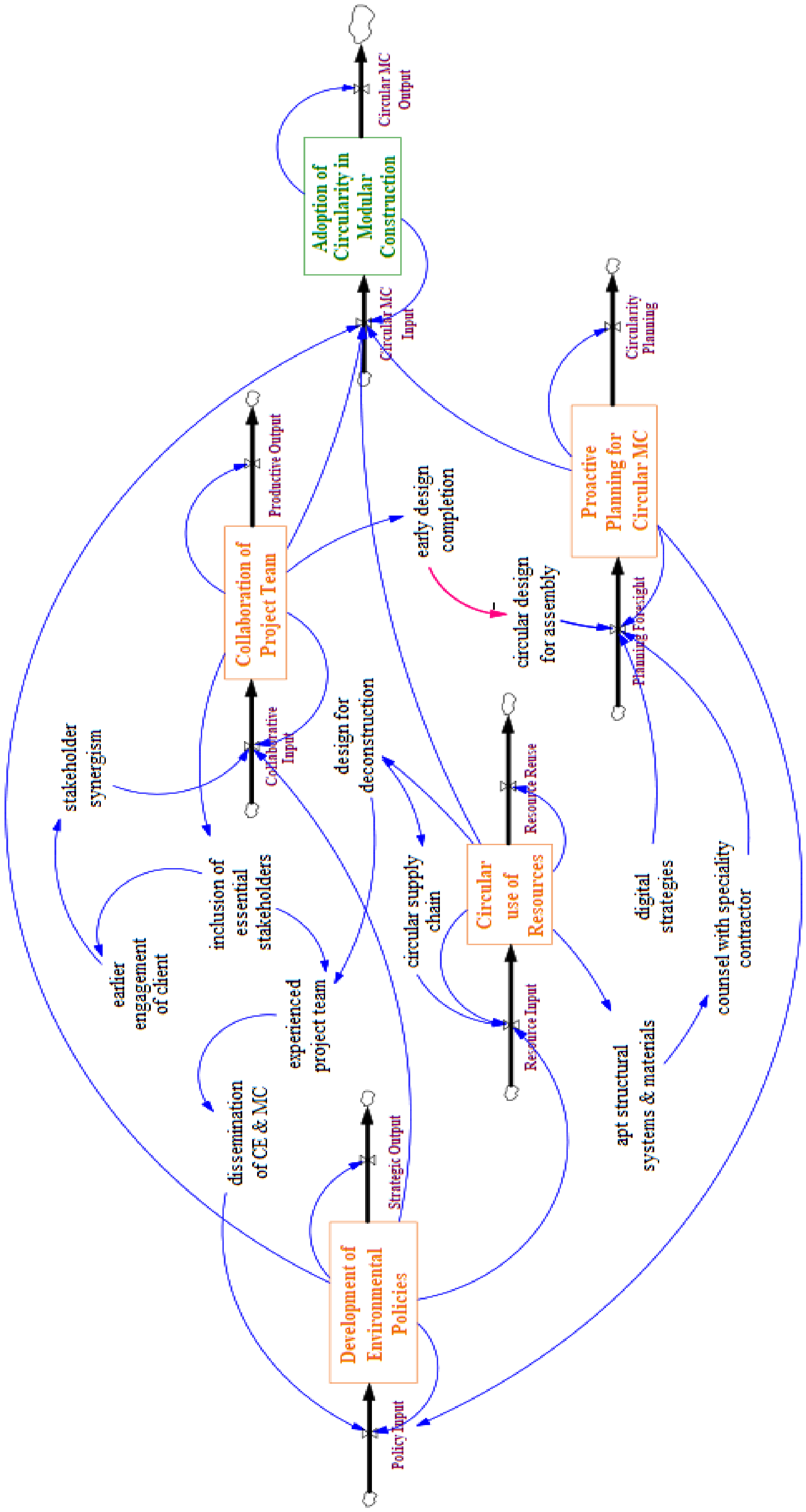
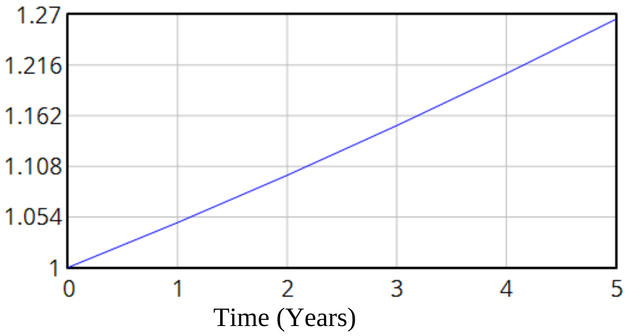
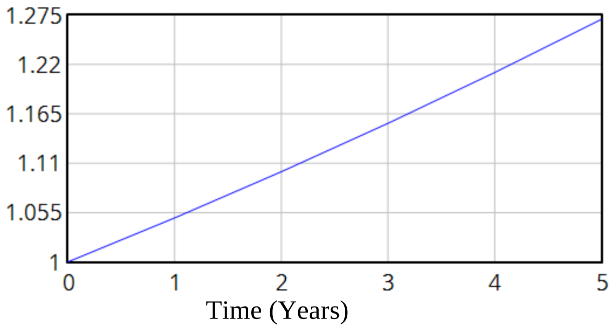


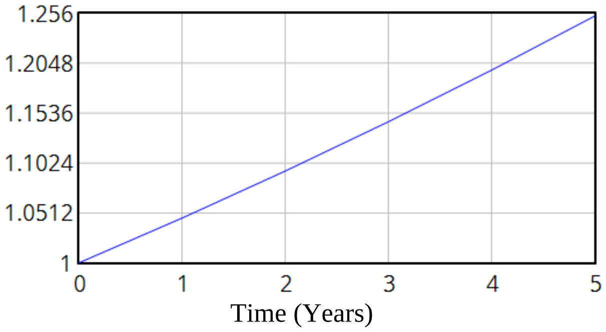
Figure 4.11: System Dynamics Model



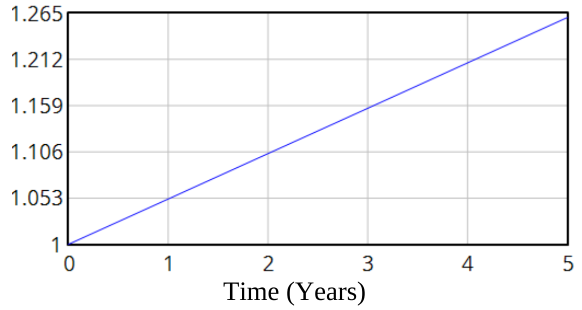
a) Development of Environmental Policies



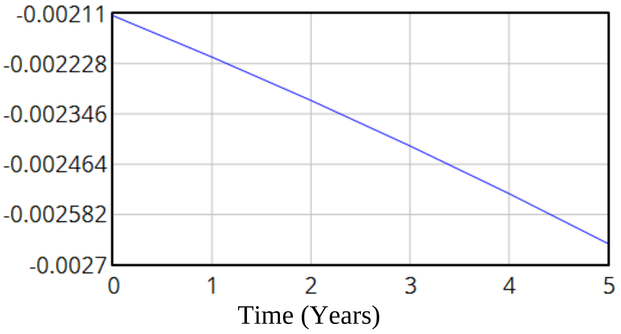
b) Circular use of Resources



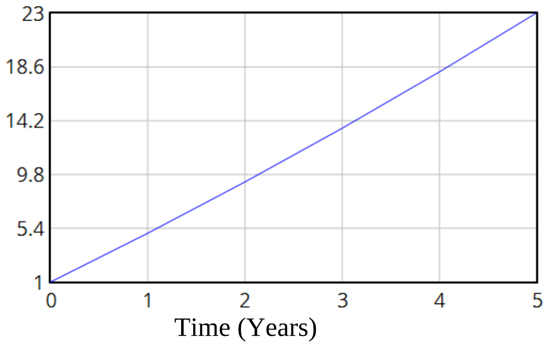
c) Collaboration of Project Team



d) Proactive Planning for Circular MC



e) Circular Design for Assembly



f) Adoption of Circularity in Modular Construction

Figure 4.12: Simulation Results

Figure 4.12(a) shows a linearly increasing upward trajectory over a span of five years for a stock named Development of Environmental policies. This gradual increase depicts the aggregation of benefits, a comprehensive and over-arching policy framework initiated by the governmental authorities could bring out. The constructive influence of the strong reinforcing loops (R2, R3 and R5) constituting factors like instigating the concept of integrating CE in MC and visionary planning for circular MC is also complementing this increased intensity over time. Similarly, Figure 4.12(b) illustrates the boost in positive impact of using the materials and resources in a cyclic manner. The intensity with which it contributes to the system within five years is justified by the support of reinforcing loops R3, R4 and R5. The intensive impact of this stock is enhanced by the integrating factors such as the utilization of materials and structural systems relevant to the concept of circular construction, deliberate design considerations for disassembly, a circular supply chain management intervened by the governmental incentives and subsidies.

Figure 4.12(c) and Figure 4.12(d) shed light on the momentous increase in intensity of a well collaborating project team and farsighted planning for CMC respectively. Several intrinsic and extrinsic factors add to the exponentially increasing impacts these stocks exert on the model. The synergy developed by the earlier and productive engagement of various crucial stakeholders can aggravate the concurrence of project teams. Just as the use of digital tools and strategies, taking inputs from manufacturers during design phase for assembly enhances the potential of proactive planning with time.

A factor can affect the system negatively on individual level as in the case shown in behavior over time graph for circular design for assembly. This negative impact is indicated by values with a minus sign and an overall dwindling behavior in Figure 4.12(e). The reason for such demeanor being the inverse relation speedy completion of design has with circular design as integrating circularity in assembly design requires enough time for deliberation. The illustration identifies locations where efforts may be required to mitigate the detrimental effects of certain factors through the years. Graphical depiction is a significant tool for analyzing the impact of contributing variables on the uptake of CMC.

With the aim of visualizing composite influence of all the pivotal factors on the ease with which circular modular construction practices can be propagated in the developing countries, a behavior over time graph for CMC is presented in Figure 4.12(f). The graph has a positive slope showing linear increase in CMC implementation in the given span of five years. It demonstrates the fact that frameworks and regulations initiated by governing bodies, combined efforts of every project team member leading to well-informed decision-making way in advance and mindful use of resources in a circular fashion can increase the potential adoption of circularity in modular construction. Other interactive factors include increased awareness among industry practitioners, earlier involvement of important stakeholders, especially the client leading to a synergistic effect. Additionally, design for assembly and disassembly using apt structural infrastructure and components whereby incorporating the input of specialty contractors as well. A supply chain inspired by the circular economy can significantly contribute to the successful transition from a linear to a circular manufacturing cycle (MC).

4.9 Model Validation

The adequacy and adaptability of a model for its designated purpose needs to be ensured. As already described in chapter 3 of this thesis, five conclusive analysis techniques were employed to validate the SD model: boundary adequacy test, parameter verification, structure verification, extreme condition verification, and sensitivity analysis.

4.9.1 Boundary Adequacy Test

The boundary adequacy test was conducted to ensure that all the relevant key factors are autogenous, and all the critical feedback loops are included in the model necessary to accurately represent the real-life scenario. Since the model dynamically adapted to all variables and changes in conditions and boundaries over time, it was deemed endogenous (Al-Kofahi et al., 2020). Field experts also confirmed that the model's responses were aligned with the real-world outcomes.

4.9.2 Structure Verification Test

For the SD model to accurately address the real time complexities associated with the application of circularity principles into modular construction, a structure verification test was performed. As all the variables were retrieved through a focused review of literature, their inter-relations were backed by industry practitioners, their feedback loops and equations were logically correct, the model can also be declared theoretically consistent and structurally sound. The field experts also reinforced the validity of the model reciprocating the actual system.

4.9.3 Parameter Verification Test

To ascertain the parameters in the model are accurate, realistic, and appropriate for the system under consideration, parameter verification was performed. Since all the definitive and mathematical parameters of model were based on credible relevant literature also approved by the concerned experts, it is evident that the model precisely reflects the real system

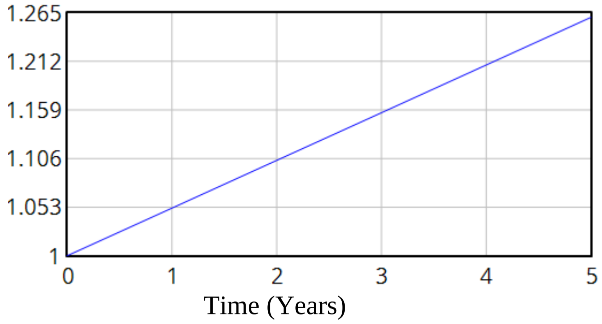
4.9.4 Extreme Condition Test

An extreme conditions test was conducted to ensure the model behaves logically and realistically when certain parameters are given extreme or unusual values. The model was subjected to exceptionally low and high values, and its response was found to align with real-time scenarios. Experts confirmed these results, thereby validating the proposed system dynamics model.

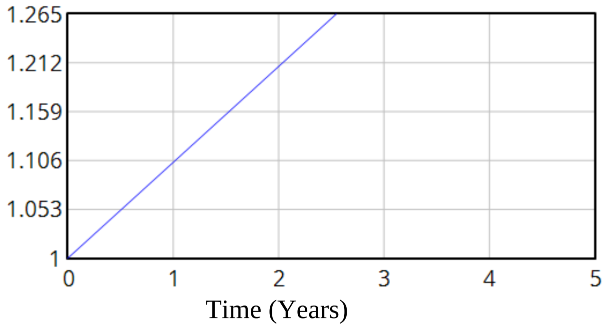
4.9.5 Sensitivity Analysis

Sensitivity analysis aims to examine the pattern of response or characteristics of the fundamental components of the model corresponding to the change in values of certain key parameters (Marimon et al., 2013). Therefore, the key variables that spur substantial responses in model state are to be identified. Values of these variables are varied, and the consequent effect is observed. While doing so, it is to be ensured that the model does not produce any unrealistic response.

The system dynamics model developed in current study was thoroughly scrutinized and a factor named ‘Adoption of Digital Strategies’ was identified to have caused the most significant impact. This parameter was defined as a constant in the model, therefore, its influence on the rest of the model components was observed by assigning various values to it.



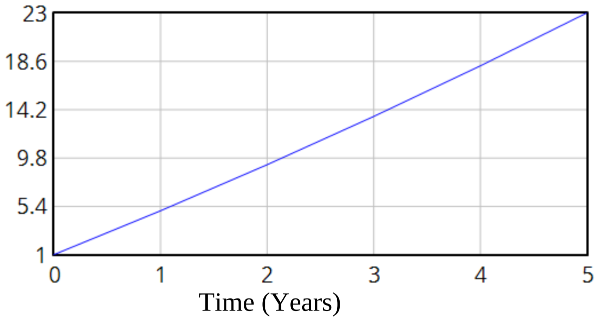
a) For initial value ‘1’



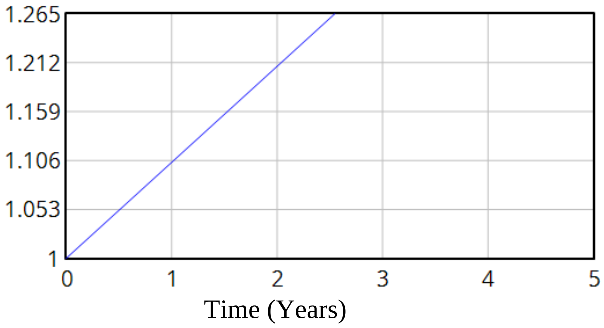
b) For final value ‘2’

Figure 4.13: Proactive planning for Circular MC affected by Digital Strategies

Figure 4.13(a) indicates the trend of proactive planning for circular modular construction when the value of constant i.e. adoption of digital strategies, was kept at ‘1’. In contrast to that, Figure 4.13(b) shows how the insightful planning will escalate when the value of parameter under consideration is increased to ‘2’ in the same span of five years.



a) For initial value ‘1’



b) For final value ‘2’

Figure 4.14: Adoption of Circular MC affected by Digital Strategies

In a similar manner, Figure 4.14(a) shows the trend line of additional stock introduced to represent the adoption of circular MC at the initial value of ‘1’ for parameter in question. In the counterpart, a slight enhancement in this adoption pattern is observed when the input value is raised to ‘2’. The impact of changing the assigned values to the given parameter representing the use of digital strategies is greater on the immediate consequent factors than the later ones. The incidental behaviours of other parameters can also be visualized in Vensim software. This result of sensitivity analysis was also acknowledged by the field experts that smart use of modern-day technologies can pave way for easier uptake of circularity approach to the linear construction model.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The current chapter aims to summarize the whole research study while focusing on the outcomes. It constitutes the results of the research, its limitations and endorsements for further research in this subject matter. It also manifests how the objectives defined in the beginning of this research have been fulfilled.

5.1 Review of Objectives

The primary objective of this study was to address the research question regarding how to tackle the complexities involved in integrating circular economy principles into a conventional modular construction framework. For the purpose of review, the research objectives are outlined as follows:

- To pinpoint the factors that contribute the adoption of circular modular construction in developing countries.
- To determine the importance, interconnectivity, and functionality of identified factors.
- To develop a SD model to cater the complexity in the adoption of circularity in modular construction to promote sustainability

5.2 Conclusions

The roadmap to achieve the said objectives involved the data retrieval from existing literature and from the industry practitioners from developing countries around the world. Accordingly, 30 contributing factors were recognized that could potentially favor the successful uptake of circular MC as a modern yet sustainable construction approach. These factors when ranked based on their field score and literature score, 20 topmost contributors were shortlisted by employing a 60/40 importance ratio with 80% cut-off point on pareto chart. The questionnaire floated among the experts working in relevant fields in various developing countries set the foundation of strength and polarity of influence each factor had on the others. The factors interrelations with RII values and polarity are summarized in Table 5.1.

Table 5.1: Preliminary List of factors influencing Circular MC

Sr. No.	**Impacting Factors**	**Impacted Factors**	**Mean**	**RII**	**N. RII**	**Polarity**
1	Experienced Project Team	Dissemination of CE & MC	4.17	0.83	0.047	Direct
3	Inclusion of Essential Stakeholders	Experienced Project Team	4.16	0.83	0.047	Direct
2	Design for Deconstruction	Experienced Project Team	4.06	0.81	0.046	Direct
4	Inclusion of Essential Stakeholders	Earlier Engagement of Client	4.69	0.94	0.053	Direct
5	Collaboration of Project Team	Inclusion of Essential Stakeholders	4.21	0.84	0.048	Direct
6	Earlier Engagement of Client	Stakeholder Synergism	4.22	0.84	0.048	Direct
7	Apt Structural System & Material	Counsel with Specialty Contractor	4.36	0.87	0.049	Direct

Sr. No.	Impacting Factors	Impacted Factors	Mean	RII	N. RII	Polarity
9	Stakeholder Synergism	Collaboration of Project Team	4.21	0.84	0.048	Direct
8	Development of Environmental Policies	Collaboration of Project Team	4.02	0.80	0.046	Direct
11	Dissemination of CE & MC	Development of Environmental Policies	4.12	0.82	0.047	Direct
10	Proactive Planning for Circular MC	Development of Environmental Policies	4.22	0.84	0.048	Direct
12	Counsel with Specialty Contractor	Proactive Planning for Circular MC	4.06	0.81	0.046	Direct
13	Circular Design for Assembly	Proactive Planning for Circular MC	4.14	0.83	0.047	Direct
14	Adoption of Digital Strategies	Proactive Planning for Circular MC	4.57	0.91	0.052	Direct
15	Collaboration of Project Team	Early Design Completion	4.01	0.80	0.045	Direct
16	Early Design Completion	Circular Design for Assembly	4.19	-0.84	0.047	Indirect
17	Circular use of Resources	Design for Deconstruction	4.31	0.86	0.049	Direct
18	Development of Environmental Policies	Circular use of Resources	4.29	0.86	0.049	Direct
19	Circular Supply Chain	Circular use of Resources	4.07	0.81	0.046	Direct

Sr. No.	Impacting Factors	Impacted Factors	Mean	RII	N. RII	Polarity
20	Design for Deconstruction	Circular Supply Chain	4.26	0.85	0.048	Direct
21	Circular use of Resources	Apt Structural System & Material	4.09	0.82	0.046	Direct

These relationships and their polarities were mapped on a causal loop diagram. Consequently, four major stocks were identified in addition to converging stock to formulate a system dynamics model. The associated equations were also fed into the model and were simulated for a duration of five years. All this was carried out using VENSIM PLE® software. The outcomes in graphical form were extracted to be analyzed. For the validation of model, multiple assessments were executed to ensure the model relatability to the real-life scenario. The same was corroborated by the experts having substantial experience in circular construction field.

5.3 Limitations

This research study had a few limitations that need to be stated. The first one being the scope, second one being the duration and the last one being specificity of the factors. This study only focused on the countries with developing economies and not on the developed ones with a sole purpose of urging these developing nations to view such novel approaches as a means of making construction more sustainable. The developing countries might have other contributing factors that can be a future research interest. Furthermore, the model simulation was carried out for a span of five years which is deemed to be an average time for a developing nation to accept and adapt to novelty in building sector. However, this time can vary from region to region depending on the local acceptability. Lastly, the factors summarized from literature were limited in number and were more general in nature. Whereas separate SD models can be developed focusing on distinct stakeholders i.e. clients, consultants, contactors, specialty contractors etc., one at a time. This may be due to their discrete apprehensions and concerns regarding a development project.

5.2 Discussions and Recommendations

A country’s economy rests its foundation upon multiple factors, out of which construction embodies the most significant potential. But at the very same time, it is the most resource consuming and waste generating sector of the industrial infrastructure. This has led to degradation of recourse reservoirs and environment. The concept of sustainability had been introduced to tackle this alarming situation, of which modular construction is also a benefactor. In recent years, the concept of the circular economy has garnered considerable attention due to its potential to transform the linear 'Take, Make, Dispose' approach into a circular '9Rs' approach. This includes Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. The idea of integrating modular construction and circular economy has gained attention only recently. This research is aimed at contributing towards the implementation of this idea in a hurdle free organized manner.

The outcomes of this study illuminate the most relevant and imperative of the various factors that can assist the industry practitioners in turning their modular construction projects into circular ones. It shows how focusing on four major perspectives i.e. environmental policies, circular usage of resources, collaboration of project team and proactive planning can have an accumulating effect on the triumphant execution of circular modular projects. Several other factors that interact with these four further strengthen the holistic impact. The following are a few recommendations based on the outcomes of SDM.

- The first rudimentary step on the way of adopting circular approaches in prefabricated construction is to ensure the wide spread of awareness, knowledge and consciousness about such practices and how they can be beneficial to all. The target audience spectrum should encompass the clients, consultants, contractors, specialty contractors, governmental authorities and principally the public who is ultimately the end user.
- Development of regulatory frameworks regarding environmental preservation i.e. pilot circular modular projects, incentives, fiscal and procurement structures.
- The project initiators should contemplate circular economy as a strategic business plan rather than only a requirement for sustainability. This encourages the project team to proactively plan for circularity of product and materials for optimal use.
- Development organizations should prioritize the employment of relevant, experienced and skilled professionals that can lead the project teams in a collaborative manner.

- The clients must explicitly specify the project objectives right at the beginning and must include the provision of integrating CE principles throughout the supply chain. A whole lot of critical stakeholders should be taken on board.
- The project team should pre-emptively plan and make use of the life-cycle approach to speculate the project performance in longer run.
- An inclusive environment should be developed to bring together all the key participants of the supply chain. Inputs from the design team, contractors, sub-contractors, specialty manufacturers and suppliers can help explore various scenarios and come up with the optimum solution.
- CE principles should be implemented in the procurement of materials and production of modules in a controlled factory environment. The products should have material passports and labels clearly stating their ability to be reused.
- At the project handover stage, the team should compare the achieved outcomes with the predetermined objectives. Moreover, to ensure continued refinement of the circular process, the project team must document the lessons learned.

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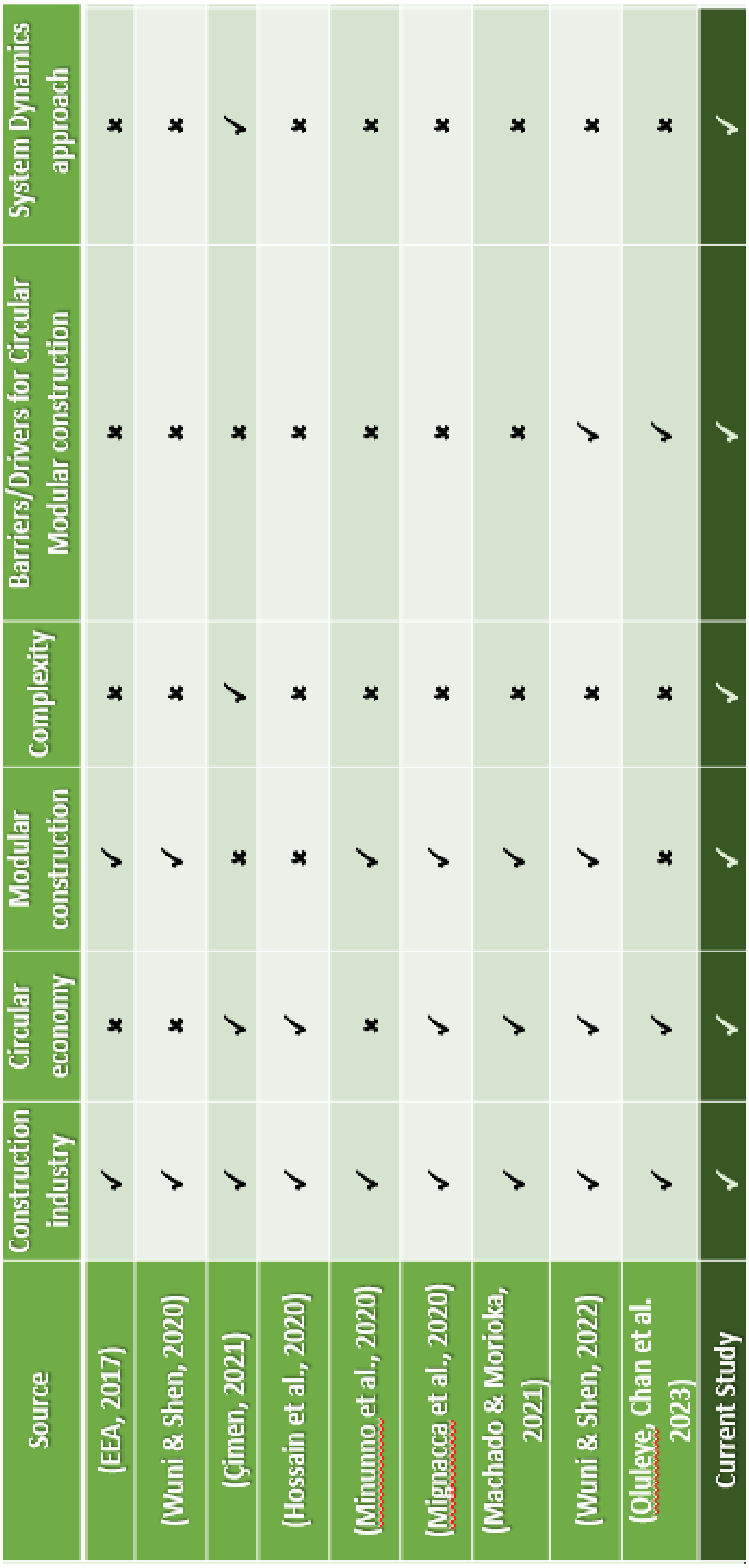
APPENDIX I



Source	Construction industry	Circular economy	Modular construction	Complexity	Barriers/Drivers for Circular Modular construction	System Dynamics approach
(EEA, 2017)	✓	×	✓	×	×	×
(Wuni & Shen, 2020)	✓	×	✓	×	×	×
(Çimen, 2021)	✓	✓	×	✓	×	✓
(Hossain et al., 2020)	✓	✓	×	×	×	×
(Minunno et al., 2020)	✓	×	✓	×	×	×
(Mignacca et al., 2020)	✓	✓	✓	×	×	×
(Machado & Morioka, 2021)	✓	✓	✓	×	×	×
(Wuni & Shen, 2022)	✓	✓	✓	×	✓	×
(Oluleye, Chan et al. 2023)	✓	✓	×	×	✓	×
Current Study	✓	✓	✓	✓	✓	✓

APPENDIX II

PRELIMINARY QUESTIONNAIR

The Adoption of Circularity in Modular Construction in Developing Countries Using System Dynamics Approach

Respected Sir/Madam,

This questionnaire survey is part of my MS thesis research titled 'The Adoption of Circularity in Modular Construction in Developing Countries Using a System Dynamics Approach.' The main objective of this survey is to identify and rank the factors contributing to the adoption and integration of the circular economy into modular construction.

The main part of this study relies on questionnaire survey. In this regard, please feel free to contact me.

Your contribution in this regard will be highly appreciated. Thanking you in anticipation.

Regards,

Aban Bukhari
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Islamabad, Pakistan.
Email: abanbukhari0000@gmail.com

*Required

1.Email address *

1. Personal Information

Please be assured that data will only be used for study purposes and no personal information will be disclosed at any forum/level.

2. Name *

3. **Please indicate your highest academic qualification *** *Mark only one oval.*

○ BTech

○ BSc/BEng

○ MSc/MEng/MTech/PG Dip

○ PhD/DEng

○ Other:

____

2.Please indicate your years of professional experience * *Mark only one oval.*

○ 0 to 1

○ 1 to 5

○ 6 to 10

○ 11 to 15

○ 16 to 20

○ 21 and above

3. Please indicate your field of work (Select all that may apply) ** Mark at least one oval.*

○ Architecture

○ Building design

○ Infrastructure management

○ Construction management

○ Quantity surveying

○ Engineering

○ Site execution

○ Project management

○ Financial consultancy

○ Other: ______________________________

4. **Please indicate your country (country of working experience) ***

____

5. **Please indicate your organization type *** *Mark only one oval.*

○ Client

○ Consultant

○ Contractor

○ Sub-Contractor

○ Specialty Contractor

○ Supplier

○ Academician

○ Other: ______________________________

Contributing Factors for adoption of circular modular construction.

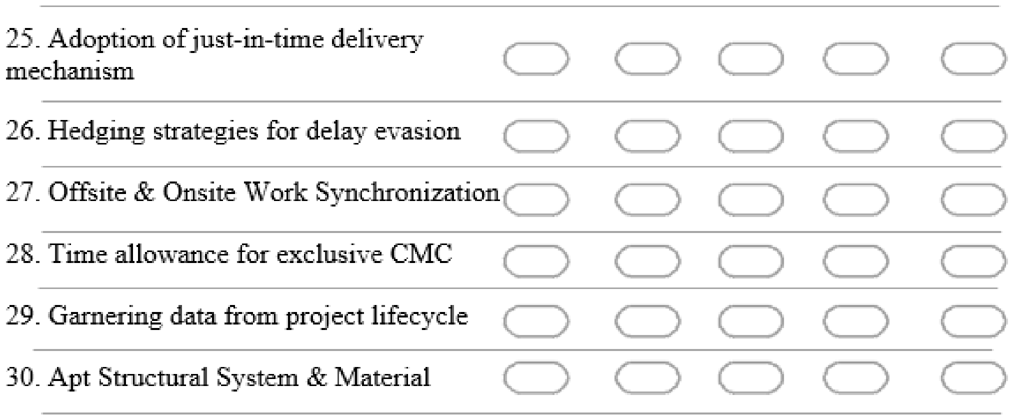
A circular economy (CE) is defined as an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration and increases waste minimization by keeping materials and resources in a closed loop. Modular integrated construction (MIC) is an innovative construction method where free-standing integrated modules, complete with finishes, fixtures, and fittings, are manufactured in a prefabrication factory and then transported to the site for installation in a building. It represents the highest level of prefabrication, involving the greatest integration of value-added factory-made prefinished modules.

Circular modular construction projects are designed, managed, constructed, and operated with the objectives of reducing, reusing, and recycling materials and building components. Circular construction practices and business models are essential to mitigating the significant impact of the construction sector on the widening global circularity gap. Therefore, it is crucial to explore methods for adopting circular construction in developing countries.

A total of 30 contributing factors for the successful adoption of circularity in modular construction have been identified from a thorough literature review. You are kindly requested to give your valuable input by rating each factor in accordance to your knowledge and experience.

8 Factors contributing towards the adoption of circularity in modular construction. * *Mark only one oval per row.*

	Very Low	Low	Medium	High	Very High
1. Dissemination of Circular Economy & Modular Construction	○	○	○	○	○
2. Skilled industry practitioners	○	○	○	○	○
3. Experienced Project Team	○	○	○	○	○
4. Earlier Engagement of Client	○	○	○	○	○
5. Inclusion of Essential Stakeholders	○	○	○	○	○
6. Stakeholder Synergism	○	○	○	○	○
7. Counsel with Specialty Contractor	○	○	○	○	○
8. Collaboration of Project Team	○	○	○	○	○
9. Vigilant use of documentation management system	○	○	○	○	○
10. Development of environmental policies	○	○	○	○	○
11. Early involvement of certification body	○	○	○	○	○
12. Proactive Planning for Circular MC	○	○	○	○	○
13. Early Design Finalization	○	○	○	○	○
14. Circular Design for Assembly	○	○	○	○	○
15. Design for Deconstruction	○	○	○	○	○
16. Adoption of digital strategies	○	○	○	○	○
17. Optimal use of Building Information Modelling	○	○	○	○	○
18. Additive manufacturing using recyclable materials	○	○	○	○	○
19. Circular use of Resources	○	○	○	○	○
20. Deliberation on critical tolerances among interfaces	○	○	○	○	○
21. Favorable site features and layout	○	○	○	○	○
22. Integrated procurement system	○	○	○	○	○
23. Circular Supply Chain	○	○	○	○	○
24. Inventory Optimization Design	○	○	○	○	○



25. Adoption of just-in-time delivery mechanism	○	○	○	○	○
26. Hedging strategies for delay evasion	○	○	○	○	○
27. Offsite & Onsite Work Synchronization	○	○	○	○	○
28. Time allowance for exclusive CMC	○	○	○	○	○
29. Garnering data from project lifecycle	○	○	○	○	○
30. Apt Structural System & Material	○	○	○	○	○

Any other factor in your opinion not mentioned in the list above