A SYSTEMS THINKING APPROACH TOWARDS REUSE

Digital Platform Ecosystem facilitating building design with recoverable elements

Master Thesis by Sreeja Raghunathan

THIS PAGE IS INTENTIONALLY LEFT BLANK]

A Systems Thinking approach towards Reuse

Digital platform ecosystem facilitating building design with recoverable elements

By
Sreeja Raghunathan (4998812)

in partial fulfilment of the requirements of the degree of
Master Construction Management and Engineering
Delft University of Technology
August 5, 2021

Author:
Sreeja Raghunathan
Student No. 4998812

University:
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Master Construction Management and Engineering

Thesis Committee:
Prof.dr.P.W.Chan (MBE) – Chair, TU Delft
Dr. ir. Martine van den Boomen (CEG) - First Supervisor, TU Delft
Dr. D.F.J. Schraven (CEG) - Second Supervisor, TU Delft
Mr. Maarten Veerman - Company Supervisor, Witteveen+Bos

Preface

This report is written to document the thesis work I conducted as part of the MSc. program in Construction Management and Engineering at TU Delft. The research was conducted in collaboration with Witteveen+Bos. Having spent three years working on thermal power plant projects back in India, I had sufficiently realized the need to embrace sustainability. While I always wanted to make a valuable contribution towards building a sustainable environment, I was unsure of how to move ahead with it. My introduction to the world of circular economy in the construction industry has piqued my interest in this topic and encouraged me to study it in depth. This research is a combined work of my passion towards circular economy and the deep desire to make an attempt towards rectifying or mitigating the damages done to the environment. This research has been a roller coaster ride and was made possible with the support of a few people. I would like to take this space and time for expressing my deepest gratitude to all these people.

To begin with, I would like to thank my graduation committee for their valuable guidance and constant support throughout the process. I express my deepest gratitude to my first supervisor, **Dr. Ir. Martine van den Boomen**, for helping me to gather my thoughts and push me in the right direction. I sincerely thank her for the time and assistance during the research and I could not have made it without her encouraging words. I would also like to thank my second supervisor, **Dr. D.F.J. Schraven** for his valuable insights. Though my interaction with him was limited, his suggestions were highly inspiring and have influenced some of the significant decisions that I had to take during the course of the research. I would further like to thank my chair, **Prof.dr.P.W.Chan**, for helping me gain new perspectives on my research. Although the Chair of a thesis committee is usually required to meet with the students during the milestone meetings, he spent additional time and efforts to help me shape the research to what it is today. I am grateful to Witteveen+Bos for having given me the opportunity to conduct my research with them. I will always be indebted to my company supervisor, **Ir. Maarten Veerman**, for having been extremely patient with me throughout this journey. He has always stood by me like a pillar of support during the uncertainties. His sincere efforts to help me with this research, which goes beyond that of a company supervisor to being a good friend, will always be cherished by me.

A special thanks to all the interviewees and the team at Witteveen+Bos for giving their valuable insights. I would like to extend my gratitude to **Ir. S.A. (Simon) Tiemersma** (Team leader at TU Delft Game Lab) for introducing me to the world of serious gaming.

Finally, I owe everything that I have achieved in my life to my parents and my brother. They have made huge sacrifices in their lives to ensure that I am able to pursue my dream. I will always be grateful to them for blindly trusting all my decisions and providing me with constant support and encouragement. Thanks a lot for believing in me and I hope to make you proud always.

Staying away from my family has not been easy for me and it would not have been possible without my friends. I sincerely thank all my friends in Delft for their constant support and for having given me some beautiful memories to cherish for a lifetime.

I wish you a pleasant read ahead!
Sreeja Raghunathan
Delft, August 2021

Executive Summary

Introduction

The construction industry of the Netherlands is known to have one of the highest recycling rates in Europe. A major proportion of all the Construction Demolition Waste (CDW) is recycled into foundation material for roads, new residential areas and industrial estates. This could lead to a misconception that the impact of construction waste has been mitigated by attaining high recycling rates. However, it was reported that only 3-4% of the total construction material for buildings comes from secondary resources. This is because the raw materials required for construction are usually available as per the demand. In addition, the terms 'Reuse' and 'Recycle' are often wrongly used interchangeably. Thus, there has been a considerable progress in reducing the environmental impacts by waste diversion, but the consumption rate of natural resources for construction material is still on the higher side. There needs to be a higher emphasis on reusing old building components in new construction without down-cycling them and by retaining their original functions.

The demolition industry is currently responsible for the supply of recovered building elements for reuse. On the other hand, the construction industry is responsible for the consumption of the recovered elements and consequently increase the demand. Much of the efforts to promote reuse is dedicated towards the promotion of pre-demolition and pre-refurbishment audits. While the significance of these efforts to enhance the supply-side cannot be discounted, it is often ignorant about the requirements of the demand side. Reusable material vendors and deconstruction contractors belonging to the supply industry are facing multiple challenges from the absence of a regulated 'system' to streamline their business processes, establish supply and demand chain and connect with designers and architects. This is leading to an eventual mismatch of demand and supply concerning the quality and quantity of reusable elements. In addition, the supply-side of the industry is often discouraged to take financial and technical risks in recovering the elements for reuse because of the uncertainty in demand. While attempts are being made to establish a market for the sale of recovered materials, the absence of a governmental regulatory framework, economical uncertainties and social perceptions are adding to the complexity of establishing a suitable system. Reusing recoverable building elements from existing buildings in new building projects is influenced by multiple factors such as technical, financial, economic, environmental and legislative. Several attempts have been made towards developing a digital solution in the form of individual product platforms to facilitate reuse. However, these solutions exist as isolated products and their ability to facilitate intervention in the reuse process is not established. This calls for a holistic approach to develop a solution which not only focuses on developing a technical tool but also focuses on embedding the solution in the process of reusing building elements.

Research Objective: The main objective of this research is thus, to investigate the application of 'Systems thinking' as a holistic approach that focuses on developing a digital platform ecosystem based on the interventions amongst the actors and processes within the system.

To achieve this objective, the main research question for this research is formulated as follows:

> ***"How can the systems thinking approach be used to develop a digital platform ecosystem for facilitating the design of new buildings with recoverable building components from existing buildings?"***

Research Methodology

This research tries to bring together three different schools of thoughts - 'Systems Thinking', 'Digital Platform Ecosystem' and 'Reuse' to propose a holistic and well-founded solution to solve the problem of reusing recoverable building elements.

Systems Thinking: In the context of systems thinking, a system is defined as follows: *"A system is an interconnected set of elements that is coherently organized in a way that achieves something (function* *or purpose). It consists of three components mainly: Elements, Interconnection of Elements and Purpose of the System."* According to this theory, complex systems present properties that arise from the interrelation between the system's components and with the environment. Systems thinking in practice encourages us to explore inter-relationships (context and connections), perspectives (each actor has their unique perception of the situation) and boundaries (agreeing on scope, scale and what might constitute an improvement).

Digital Platform Ecosystems: Digital Platform Ecosystems can be seen as an ecosystem emerging around a focal platform that provides a combination of hardware,software, infrastructure, organizational and social rules that connects actors around the platform.

The aim of this research is to propose the development of a digital platform ecosystem using systems thinking approach. The 'Systems thinking and modelling' framework used in this research consists of four major phases as shown in the diagram given below. Phase 1 focuses on structuring the problem and analyzes the issues in detail. This is followed by deriving the key drivers of change based on the stakeholder interviews. The inputs from the stakeholder interviews was also used as an input to develop multiple project scenarios which were used to develop game scenarios in the next phase. A simple online board game was developed to simulate the conditions of building project integrated with recovered elements from an existing stock. Based on the response from the game, the key variables were derived. Key variables are basically the causes and effects of multiple scenarios encountered in such a project. These variables were used as input to develop the 'Causal Loop Diagram' for synthesizing results.

Causal Loop Diagram: Causal Loop Diagram (CLD) are tools of systems thinking approach used to map out the structure of a system to understand how behaviour has been manifesting itself in a system, so we can develop strategies to work with or counteract the behaviour. The basic logic behind these diagrams is demonstrating the causalities between two variables.

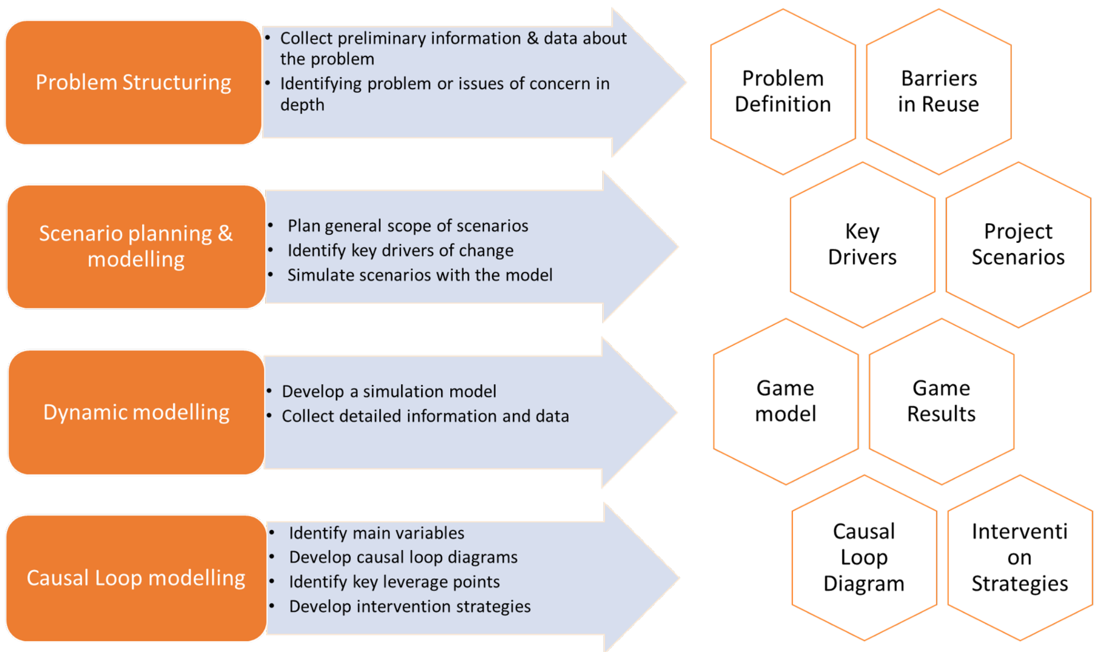

Figure 1: Systems Thinking - Research framework

Results

Based on the results from the game play session, it was found that there are 45 variables affecting the dynamics of a Building Reuse system. By connecting these variables based on their inter-relationships, the CLD was developed which contains a total of 10 feedback loops. Among these feedback loops, 6 loops are reinforcing loops while the remaining 4 loops are balancing loops. The diagram revealed that the system is based on a series of reinforcing feedback loops that reinforce the power from the demand side of the market to the supply side and vice versa. It can be concluded that the digital platform ecosystem for enhancing reuse will fundamentally rely on the intervention strategies corresponding to the reinforcing loops. Ideally, implementation of the intervention strategies corresponding to these reinforcing feedback loops should guarantee an exponential growth of the platform ecosystem. However, upon critically analyzing, the diagram revealed that the platform cannot attain an ever increasing growth with the application of these strategies. The CLD contains 4 balancing loops which can lead to the collapse of the model and must be given special attention while designing the platform. The 6 reinforcing loops and the 4 balancing loops are enlisted below:

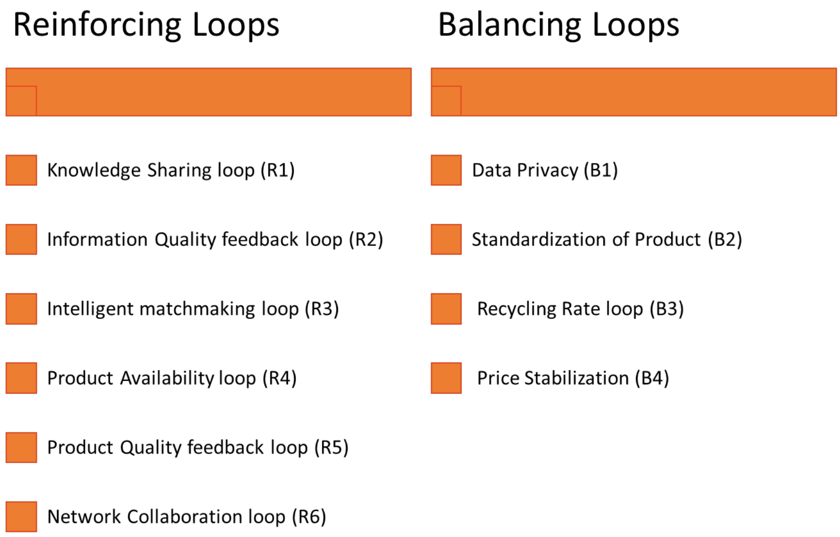

Figure 2: Results from CLD

Conclusion

In conclusion, this research demonstrated the application of Systems Thinking (ST) as a problem-solving approach to enhance the reuse of recovered building elements in new construction projects. Enhancing the reuse of building elements is a complex problem with several layers and multiple dimensions. Most of the existing solutions in the industry focus on developing individual products and tools. This is a reductionist approach where complex problems are broken down into smaller issues and solutions are developed to solve each issue. However, ST theory proposes to go the other way round and advises to embrace the complexity. The holistic approach revealed the interrelationships and dependencies of all the elements within the 'Building Reuse System' which are not otherwise addressed in a reductionist approach. Besides, the research proposes to exploit the advantages of a digital platform ecosystem. Digital platform ecosystems focus on developing a business model with digital technologies as the lifeline. By building on the intervention strategies identified, four propositions of change were given by comparing the existing scenario of the industry to the desired structure of a digital platform ecosystem. The propositions are enlisted below:

- Proposition 1: Development of a Decentralized Digital Platform Ecosystem
- Proposition 2: Shifting to Value-drive ecosystem
- Proposition 3: Creating a Reinforcing Growth model
- Proposition 4: High autonomy of the Complementors

To assist these propositions, the structure of a possible Digital Platform Ecosystems (DPE) is described along with a diagrammatic representation as shown in figure 33. The research is concluded with the acknowledgement that implementation of the intervention strategies will require certain adaptations in the system. A conclusive, but not exhaustive list of recommended adaptations in the design process and actor-network is provided to accompany the interventions strategies.

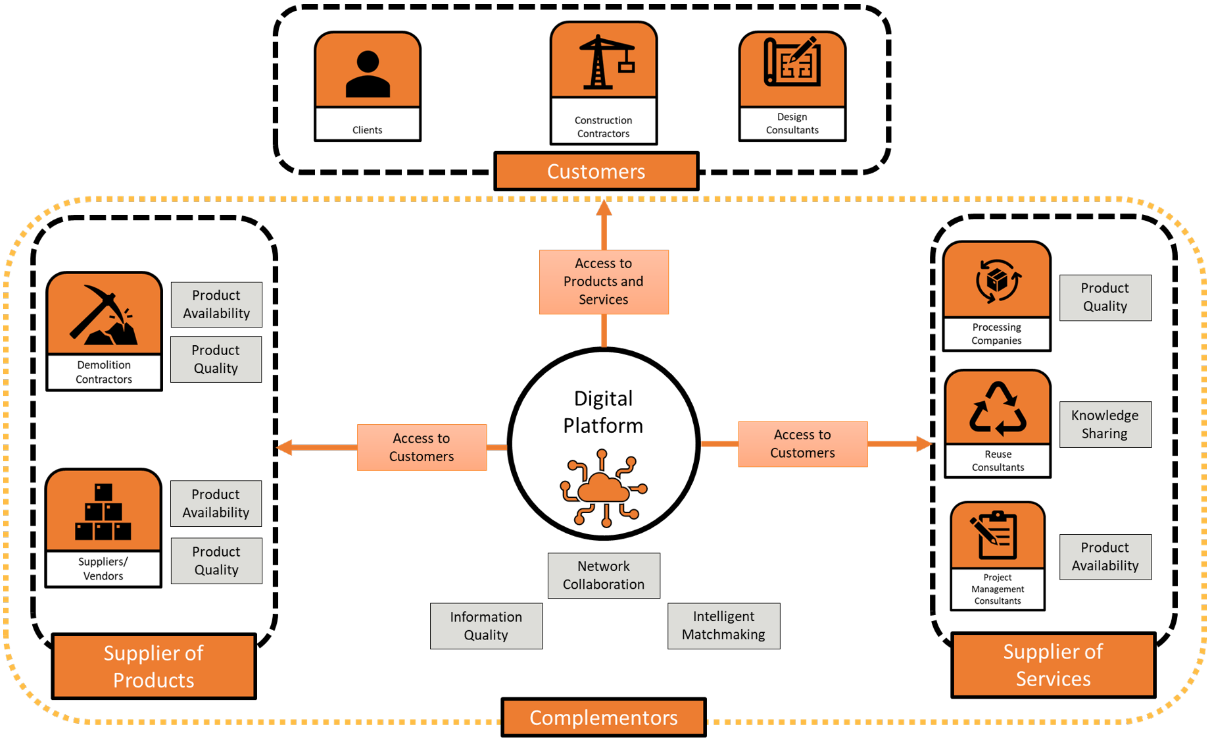

Figure 3: Proposed Digital Platform Ecosystem

Limitations and Future recommendations

CLD that was developed to visualize the 'Building Reuse System' as a whole was predominantly based on the inputs from the actors of only one of the sub-systems - 'Building Design Management system'. The CLD may be developed further by taking inputs from multiples stakeholders associated with the problem. The final phase of the proposed research methodology framework deals with the implementation of the proposed intervention strategies. The research was concluded with the proposal of certain changes to the existing approach in the industry. Testing the validity of the strategies through implementation remains a limitation. The four propositions based on the intervention strategies identified in this research can be evaluated through experimentation. Development of experimental digital platform ecosystems along the lines of 'living labs' is a possible way of validation. The ST approach recognizes that systems are highly dynamic. Depending upon the changes in time and external environment of the system, the inter-relationships amongst the variables can change. The variables and their inter-relationships of a CLD model can be converted to mathematical equations and these can be analyzed numerically to reveal concrete patterns. Such quantitative analysis can provide better control on the system dynamics. Platforms such as 'Vensim' offers tool to facilitate such analysis. The scope of this research is limited to the boundaries of the system defined for this study. Thus, it has not accommodated other phases of a building project such as construction, operation, maintenance and use phase. The life cycle of any building element is not restricted between the deconstruction an design systems as depicted in this research. The research can be further extended by taking into consideration different phases of a building life cycle.

Contents

List of Figures

List of Tables

Acronyms

BAMB Buildings As Material Banks
BIM Building Information Modelling
CDW Construction Demolition Waste
CE Circular Economy
CLD Causal Loop Diagram
DfD Design for Deconstruction/Disassembly
DPE Digital Platform Ecosystems
GHG Greenhouse Gas
SQ1 sub-question 1
SQ2 sub-question 2
SQ3 sub-question 3
SQ4 sub-question 4
ST Systems Thinking
TGD Triadic Game Design

Chapter 1

Introduction

1 Introduction

1.1 Reading guide

This thesis consists of 12 chapters in total. Chapter 1 begins with giving a background to the problem under discussion. In Chapter 2, the problem context is analyzed in-depth to identify the research gap and develop the corresponding research questions adopted to solve the research gap systematically. This is followed by explaining the theoretical background of the research methodology in Chapter 3 and the research methodology itself in Chapter 4. Chapters 5, 6, 7 and 8 discuss the results corresponding to the four sub-questions of the research. Chapter 9 tries to establish the validity of the results by tracing back to the research gap. In Chapter 10, the answer to the main research question is defined based on the outcomes of the sub-questions. Few recommendations are given to support the results in Chapter 11 and finally, the implications of this research are discussed in Chapter 12. All the additional information to support the thesis content is attached as an appendix to the report after the references.

1.2 Background

The construction industry has been established to be the largest contributor to environmental degradation. This environmental degradation can be attributed to several aspects of the construction industry; namely, the consumption of raw materials for new construction ((Bertin et al., 2020), (Rakhshan et al., 2020), (Bertin et al., 2019)), the generation of CDW ((Ali et al., 2013), (Ginga et al., 2020), (Rakhshan et al., 2020), (Rose & Stegemann, 2018)) and the Greenhouse Gas (GHG) emissions ((Ginga et al., 2020), (Bertin et al., 2020), (Bertin et al., 2019), (Rakhshan et al., 2020), (Rose & Stegemann, 2018)) during the life cycle of a building. The construction industry is responsible for 30% of the extraction of natural resources (Rakhshan et al., 2020) as well as 25% of solid waste generated in the world (Benachio et al., 2020). Several papers have been published emphasizing the detrimental impacts of construction processes and activities on the environment. These problems are mainly associated with the linear economy model which has been traditionally followed by the industry.

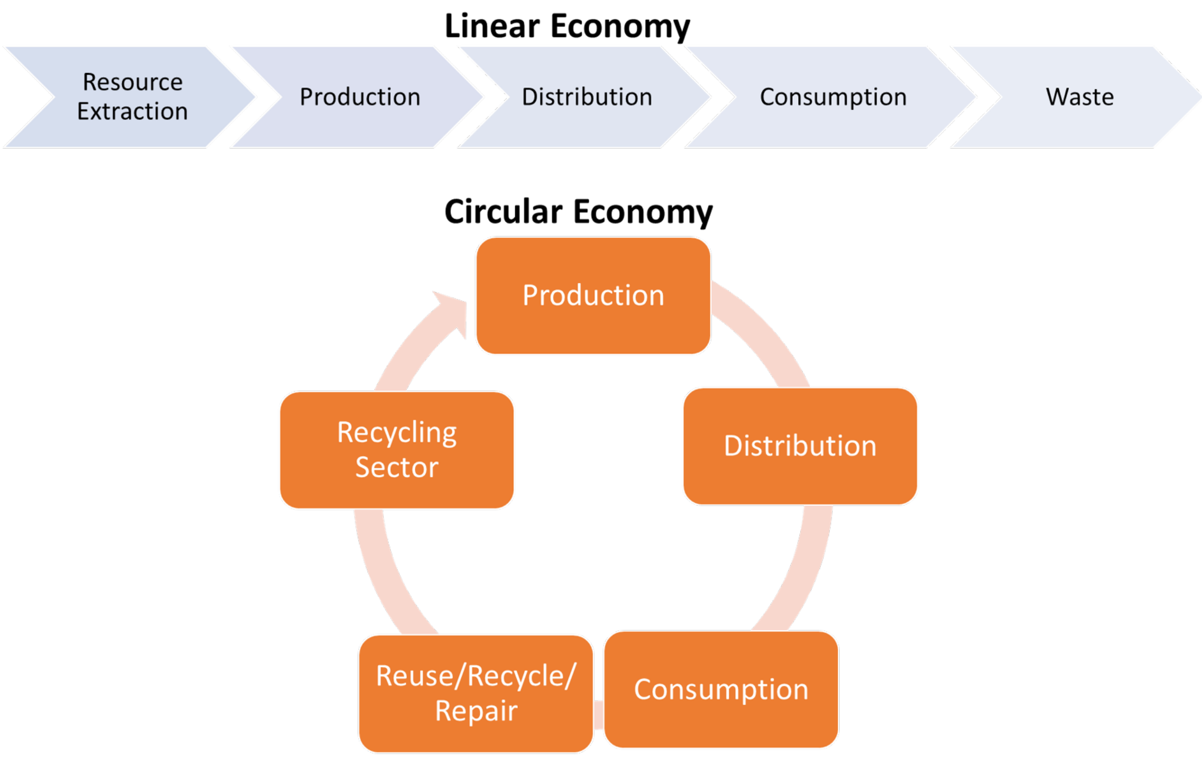

Figure 4: Linear Economy to Circular Economy (own illustration, based on (*The Circular economy - AkzoNobel Report*, 2015))

The linear economy model is based on the idea of take-make-dispose (Foundation, 2013). In this model, the raw materials are processed to become construction materials that are assembled in ways that cannot be deconstructed (Benachio et al., 2020). At the end of a building life cycle, these materials often end up in landfills or are incinerated, adding to the environmental degradation, as shown in Figure 4. As a result of the growing concerns, a paradigm shift from a Linear economy model to a Circular economy model is inevitable.

"A Circular Economy (CE) can be defined as an economic model aimed at the efficient use of resources through waste minimisation, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socio-economic benefits" (Morseletto, 2020). Although the concept of CE has been in discussion for over a decade now, the complexity and largeness of the construction industry pose several challenges before its effective materialization. The core principle of the circular economy revolves around the 'R' framework or the 'waste hierarchy' framework (*Waste prevention and management - Environment - European Commission*, n.d.). The four levels of waste hierarchy framework in decreasing order of their effectiveness in contributing towards circular economy (Kirchherr et al., 2017) is as shown in Figure 5.

Strategy	Description
Reduce	Discussion around refusing, rethinking, redesigning (including prolonging the lifespan of products), minimization, reduction, prevention of resource use and/or preserving of natural capital.
Reuse	Discussion around reusing (excluding waste), closing the loop, cycling, repairing and/or refurbishing of resources.
Recycle	Discussion around re-manufacturing, recycling, closing the loop, cycling and/or reuse of waste.
Recover	Discussion around incineration of materials with energy recovery.

Figure 5: Waste Hierarchy framework (own illustration, based on (Kirchherr et al., 2017))

While the focus of this thesis is mainly on the 'Reuse' strategy of the framework, these terms are often met with ambiguity and are used interchangeably. In the following paragraphs, a brief explanation of each of the above-mentioned strategies of the Waste Hierarchy Framework (Figure: 5) is given.

Reduce: The 'Reduce' strategy focuses on reducing the generation of CDW by adopting practices such as the use of low waste technologies and waste reduction through multiple innovative design methods (Guerra et al., 2020). The concept of waste reduction through design has received significant attention in the studies as it is estimated that one-third of the CDW could arise from poor design decisions (Osmani, 2012). Different design strategies have been developed and discussed in the research papers like Design for Deconstruction/Disassembly (DfD), design and use of modular buildings, design for adaptability of existing buildings, etc. In addition, the strategies related to conscious material selection/substitution to reduce the net contribution towards waste and GHG emissions is receiving traction (Eberhardt et al., 2020). 'Design for Reuse' is an emerging concept considered as an extension to DfD. The design methodology of DfD is mainly concerned with designing buildings that can be easily disassembled in the future for efficient recovery. On the other hand, 'Design for Reuse' takes this idea one step ahead. It gives sufficient attention to designing buildings with effective reuse of the recovered building elements (Bertin et al., 2020).

Reuse: The next available strategy in the hierarchy is the reuse of CDW, which implies using building components more than once without major processing for the same purpose or a different purpose than initially proposed. With the increasing quantity of CDW and limited availability of landfill sites across the world, the construction wastes are not effectively managed in the majority of the countries. The practice of recycling materials from construction waste to be used in new infrastructural construction has been in the industry for some time in the recent past. Several companies are involved in the retrieval, storage and sale of materials extracted from construction waste. However, these practices thrive on down-cycling the original value of materials which is contrary to the reuse ideology of the circular economy model. In the Reuse strategy, at the end of a building life cycle, the components and parts are deconstructed, to act as material banks for new buildings, keeping the components and materials in a closed-loop (Hopkinson et al., 2018). Thus, the focus is on reusing building components and materials by upholding their stated purpose, which is also termed as directing the materials from cradle-to-cradle. The theory behind reuse has established significant advantages as the net consumption of energy and resources is much less due to the minimum processes involved.

Recycle: The next available strategy of 'Recycle' is less preferred as it generally reduces the quality of the product, the opportunities for direct reuse and economic value. As mentioned before, the strategy thrives on down-cycling the original value of building elements. The CDW is subjected to several processes and the recycled material forms a certain percentage of the final product in which it is used. Thus, recycling involves high consumption of energy and resources due to the processes involved. While recycling has been prominent in the industry, the strategy of reuse is still at a nascent stage of development. There is a common misunderstanding between the usages of 'Reuse' and 'Recycle' as strategies at the end of a building life cycle. These are often considered together and presumed to be interchangeable strategies. However, in reality, these are competing choices for the continuing use of resources (Hobbs & Adams BRE, 2017).

Recover: The strategy of 'Recovery' mainly focuses on the recovery of energy from residual materials through incineration. It implies that CDW can be turned into fuel for manufacturing processes or equipment designed to produce energy. Several mechanical, caloric and biological systems and technologies can convert or process wastes into new materials or energy (*Reduce, Reuse, Recycle and Recover Waste: A 4R's Guide*, 2008). As compared to the previous strategies, recovery has received less attention in the studies. The term 'recovery' is often used to imply the recovery of materials for reuse or recycling. It could be one of the reasons for not highlighting the recovery strategy as a distinct waste management strategy.

***NB:** At this stage, it is important to highlight that 'Design for Reuse' should not be confused with the 'Reuse' strategy mentioned in this research. 'Design for Reuse' is strictly focused on the design of new reusable buildings for the future; whereas the focus of this research is to enhance the use of recovered elements from existing buildings which are not generally designed for the purpose of deconstruction and reuse. This type of reuse is accompanied by multiple challenges and barriers and have been studied extensively in the literature.*

1.3 Dutch Construction Industry

The construction industry of the Netherlands is known to have one of the highest recycling rates in Europe. A major proportion of all the CDW is recycled into foundation material for roads, new residential areas and industrial estates (Schut et al., 2015). This could lead to a misconception that the impact of construction waste has been mitigated by attaining high recycling rates (Rose & Stegemann, 2018). However, it was reported that only 3-4% of the total construction material for buildings comes from secondary resources (Herczeg David McKinnon Leonidas Milios & Klaassens Katarina Svatikova Oscar Widerberg Rotterdam, 2014). This is because the raw materials required for construction are usually available as per the demand. In addition, the terms 'Reuse' and 'Recycle' are often wrongly used interchangeably. Thus, there has been a considerable progress in reducing the environmental impacts by waste diversion, but the consumption rate of natural resources for construction material is still on the higher side. There needs to be a higher emphasis on reusing old building components in new construction without down-cycling them and by retaining their original functions. The Ministry of Infrastructure and the Environment of the Netherlands published a report titled 'Circular Economy in the Dutch construction sector' in the year 2015 (Schut et al., 2015). This report gives a detailed explanation about the vision of Dutch construction sector towards high-quality use and reuse of materials in circular economy (Schut et al., 2015). As a result, several pilot programs, prototypes and processes have been initiated within the country. These have been discussed briefly in section 2.2 of the next chapter.

Chapter 2

Problem Context & Analysis

2 Problem Context and Analysis

In the previous chapter, a general understanding of the concept of reuse and its significance in reducing the environmental impacts of the construction industry was provided. This chapter begins by explaining in detail the relevance of the problem for the construction industry through understanding the intrinsic value of existing building stocks. This section is followed by a detailed study of the current state-of-the-art solutions and their limitations within the research context. The chapter concludes with the introduction to the research gap, the research objective and the research questions formulated to address the problem at hand.

2.1 Existing buildings as Material banks for the future

The concept of 'Reuse' is receiving increasing attention in academic research. There has been significant focus on how new buildings can be designed for reuse in future. However, these studies are focused on new design methods such as DfD, design for manufacture and assembly, design of modular buildings, etc. The buildings constructed with such principles can be easily deconstructed in future and their components can be reused. Considering that a building's average lifetime is around 60-70 years, it will be several decades from now when the reusable potential of these buildings can be explored. On the contrary, the existing buildings, which are already nearing the end of the life cycle, can act as huge reservoirs of materials and components, which upon extraction be used as a substitute of raw materials (Gorgolewski & Morettin, 2009). These buildings which were designed several decades ago are generally not very energy efficient and hence are expensive to maintain concerning cost and energy consumption. These are substantial in number and have large amounts of potentially recoverable materials (Tingley & Davison, 2011). Deconstruction of these buildings can assist in the removal of existing, non-efficient buildings and the retrieved secondary building components can be reused. Reuse of many components from old buildings can significantly reduce the life cycle environmental impacts of new buildings.

The linear economy model has been prominent in the construction industry for a long time. Successful attempts in reusing the components from existing buildings as a replacement for new building components is fairly limited to a few case studies. The architects or designers viewed their buildings as 'permanent structures' and not much thought was put into understanding the fate of structures at the end of their life cycle (Ali et al., 2013). For the reuse of recoverable building elements to become a normal practice in the construction industry, it still needs to overcome several challenges in different domains. These challenges have been discussed in detail in Chapter 5. However, it is to be acknowledged that there have been multiple attempts in the Dutch construction industry towards establishing a circular economy. The concept of Urban Mining has been developed to promote the systematic reuse of anthropogenic materials from urban areas and includes exploration and observation of materials in buildings and infrastructures (Klinglmair & Fellner, 2010). Efforts in the direction of tools such as 'Scan to BIM' which are intended to digitize existing building stocks and support urban mining are at the budding stage. Several other solutions are still at a nascent stage of development and they are focused on circular economy in general. A thorough analysis of such attempts towards solving the problem of reuse in particular as opposed to a circular economy is conducted and is briefly described in section 2.2 of this chapter.

2.2 Current State-of-the-art solutions

Detailed desk research was conducted on the state of the art pilot programs, platform prototypes and practices revolving around the concept of reuse. The following section discusses the most prominent projects being undertaken in the Dutch construction industry and their significance within this research context.

Material Passports: Material Passports is a relatively new term and not many research articles are published concerning the concept. Material Passports state the material content of the products and describe how the stated materials can be reused, redesigned or recycled at the end of the product life cycle (Miu, 2020). The first mention of material passport was by Maayke Aimée Damen in the article 'A Resources Passport for a Circular Economy' (Damen, 2012). The article focused on exploring the content and format of a resources passport to successfully contribute to the achievement of the circular economy. Another important scientific contribution towards the topic of material passports is the BIM-based material passport. The BIM-based material passport is an optimization tool in early design stages and acts as an inventory at the end of the life-cycle of a building, therefore serving as a basis for a secondary raw materials cadastre (Honic et al., 2019).

While the concept of material passports is an integral element in establishing a circular industry, their reliability highly depends on the reliability and accuracy of the data that it contains. Ideally, a passport is best developed before or during the production of a product (Miu, 2020). Developing material passports for existing buildings nearing the end of the life cycle is challenging due to the difficulty in retrieving accurate and sufficient data. Thus, when dealing with existing buildings, there must be more focus on the process of retrieving data than the structure of the passport itself. Moreover, material passports are solely focused on inventory. Although it is highly essential to track and store building information for efficient decision-making, problems revolving around reuse are much more layered. The lack of information is accompanied by several other problems such as demand-supply mismatch, absence of standards and regulations, high costs, etc. While there is no ignoring the necessity of material passports for a circular economy, the issue still needs to be addressed at several other levels.

Madaster: The 'Madaster' platform provided by Madaster Foundation, a non-profit Dutch legal entity, is focused on registering, documenting, storage and exchange of data regarding the materials, components and products used in the construction industry (*Home - Madaster*, n.d.). The fundamental function of this platform is thus, the development of material passports and assuring the complete documentation of the built environment. In addition, it assists in calculating the circular value and financial value of the buildings based on the inputs. The platform caters to a wide range of owners such as contractors, developers, architects, engineers, online marketplaces and deconstruction or harvesting companies. Madaster holds a long term vision of enabling the reuse of building components and materials by utilizing the building life cycle data provided by the material passports. Madaster has the potential to grow into an established digital platform ecosystem in future based on their vision. However, their latest release notes (Madaster, 2021) and road map for 2021 (*Home - Madaster*, n.d.), indicates that their current efforts are strictly restricted to improving the functionalities and quality of the database structure. The significance of developing material databases cannot be overlooked as the successful reuse of any material largely depends on the available information. However, this information can add value to the industry only when it reaches the relevant stakeholders through commercialization. In 2018, a pilot project was executed which involved the circular demolition of an Erasmus MC building campus. The project made use of the Madaster platform to develop material passports and thus evaluate the reuse potential of the building. In this case, too, the value added by the platform was restricted to the material passport. In the concluding report of this project (*DEMOLITION FIRST ERASMUS MC BUILDING - Madaster*, 2018), it was emphasized that the large scale implementation of building reuse will only be possible with centralization, clarity on the demand and supply, accessible and exchangeable information for all parties and a shared sense of urgency. Thus, there is a need to rise above the sole development of material databases and divulge into other factors responsible for shaping a larger ecosystem.

Excess Materials Exchange: Excess Materials Exchange is a digital matching platform where the focus is on finding high-valued reuse options for materials or (waste) products for companies (*Excess Materials Exchange*, n.d.). The basic ideology of the platform revolves around developing a resources passport (material passport) for any product based on the inputs from the clients. Through the intelligent matchmaking feature, the clients are matched with potential customers with an interest in high-value reuse. The platform can aid the suppliers of waste products in accessing the potential buyers and thus enhance reuse. Within the pilot program of the platform, it has demonstrated few successful cases of matchmaking. However, these projects were restricted to individual products with no external complications like ceiling tiles and railway sleepers. The applicability of the platform to deal with highly complex building structures with several uncertainties regarding strength, environmental implications, safety, multiple stakeholder involvement, multiple supply chain networks, etc., has not been established yet. In addition, the concept is highly dependent on the development of resources passport. The limitations regarding the passports for existing buildings as discussed in section 2.2 will become a hindrance in this case as well. Besides, the platform caters to the supplier network and acts as a mediator to identify potential customers. Focusing only on the supplier side will limit the potential of the platform to cater to the needs of the demand side and eventually lead to a mismatch in the supply-demand ratio. In addition, the marketplace containing all the product information is only accessible to the users of the platform. This type of closed or one-sided network can hinder the establishment of a well-functioning market. Finally, the pilot project concluded by stating that developing tools alone is not sufficient to realize the paradigm shift (Excess Materials Exchange, 2019). There needs to be a holistic approach towards developing solutions that can grow beyond individual tools and platforms.

Buildings As Material Banks (BAMB): BAMB is an EU funded Horizon 2020 project in which 16 European countries are working together towards the mission of investigating and creating circular solutions for the built environment sector (Cornet et al., 2016). This project focuses on improving the availability and robustness of data to facilitate future reuse at a building, system, product and material levels (Hobbs & Adams BRE, 2017). Since their focus is to support the reuse of buildings in the future, the applicability of their solutions towards the reuse of existing buildings is debatable. Another Horizon 2020 project called 'Holistic Innovative Solutions for an Efficient Recycling and Recovery' (HISER) of Valuable Raw Materials from Complex Construction and Demolition Waste has the goal to formulate, develop and test novel harmonized cost-effective methodological solutions and tools facilitating the data gathering and data processing on types, qualities and quantities of building waste materials for a highly efficient selective sorting at source during the execution of demolition and refurbishment works (*HISER Project | Novel harmonized methodological solutions and tools*, n.d.). The focus of the project is mainly on waste management and has the potential to partially address the problem by regulating and standardizing the process for the demolition industry. In this case, too, a holistic approach to connecting different sectors of the industry, addressing the associated complexities is found to be missing.

Knowledge Sharing Platforms: The idea behind knowledge sharing platforms is to collate information about the circular economy to create awareness amongst the society at large. One such example is, the 'Cirkelstad' which is an attempt to bring together different stakeholders interested in contributing to the cause of circular economy in the Netherlands. Their main aim is to develop solutions through open dialogue and generate different perspectives based on their respective expertise (*Over ons - Cirkelstad*, n.d.). Platform CB'23 is another such initiative focusing on drawing up national, construction sector-wide agreements on circular construction before 2023 (*About Platform CB'23*, n.d.). Such efforts are a necessity to steer the actors of the industry towards the direction of circular economy in general.

Conclusion:
In conclusion, the above-mentioned projects are highly important to create a significant impact within their domains of focus. The purpose of this study is not to discount the relevance of these projects but to critically analyze them as a holistic solution for the problem at hand. It was observed that the majority of the solutions are oriented towards the development of material database and a few of them towards waste management. However, in practicality, the problem of integrating recovered elements from existing buildings into new construction projects has multiple dimensions. The following section is focused on addressing these in detail and establishing the need for a holistic approach.

2.3 Need for a System

Currently, the demolition industry is responsible for the supply of recovered building elements for reuse. On the other hand, the construction industry is considered responsible for the consumption of the recovered elements and consequently increase the demand. Much of the efforts to promote reuse is dedicated towards the promotion of pre-demolition and pre-refurbishment audits (Hobbs & Adams BRE, 2017). While the significance of these efforts to enhance the supply-side cannot be discounted, it is often ignorant about the requirements of the demand side. Reusable material vendors and deconstruction contractors belonging to the supply industry are facing multiple challenges from the absence of a regulated 'system' to streamline their business processes, establish supply and demand chain and connect with designers and architects (Kamal Ali, 2013). This is leading to an eventual mismatch of demand and supply concerning the quality and quantity of reusable elements. In addition, the supply-side of the industry is often discouraged to take financial and technical risks in recovering the elements for reuse because of the uncertainty in demand. While attempts are being made to establish a market for the sale of recovered materials, the absence of a governmental regulatory framework, economical uncertainties and social perceptions are adding to the complexity of establishing a suitable system.

The efforts of the supply industry will show substantial results only when there is motivated efforts from the demand side of the industry. Several studies have focused on waste management and waste diversion from construction sites. However, not many studies have invested in understanding the role of architects and designers in waste prevention or reduction by incorporating recovered building components in new construction designs. While the demolition practices have shifted to deconstruction practices, little information is available in adapting the design practices to accommodate recovered building components. The notion that waste management only belongs to the demolition industry must change and it should be accepted as a shared responsibility. This needs multiple technical and process changes within procurement and design processes to successfully tap into the existing stocks of buildings (Gorgolewski, 2019). Architect Jeanne Gang suggests that "By proposing a building made from materials at hand, the project introduces an entirely new paradigm for a project delivery process that has not changed substantially in the last fifty years. It radically alters the way a building is both conceived and made: form follows availability" (Ruby & Ruby, 2010).

Considering the above factors, it can be established that fulfilling the target of reuse is possible only when the issue is addressed from different viewpoints such as technical, environmental, social, financial and regulatory, taking into consideration both sides of the industry. Thus, a shift in the fundamental approach of addressing reuse from a supply-oriented approach to a more holistic approach is essential.

2.4 Research Gap

Exploration of the problem context resulted in the conclusion that reusing recoverable building elements from existing buildings in new building projects is influenced by multiple factors such as technical, financial, economic, environmental and legislative. Several attempts have been made towards developing a digital solution in the form of individual product platforms to facilitate reuse. However, these solutions exist as isolated products and their ability to facilitate intervention in the reuse process is not established. This calls for a holistic approach to develop a solution which not only focuses on developing a technical tool but also focuses on embedding the solution in the process of reusing building elements.

Research Objective: The main objective of this research is thus, to investigate the application of 'Systems thinking' as a holistic approach that focuses on developing a digital platform ecosystem based on the interventions amongst the actors and processes within the system. The concept of systems thinking is usually applied when the problem to be addressed is highly complex and has multiple dimensions. Chapter 3 discusses in detail the concept in itself and tries to relate the problem characteristics to a complex issue as looked through the lenses of the 'systems thinking' approach.

2.5 Research Questions

To achieve the objective stated in the previous section, the following research questions are formulated. The thesis is broadly divided into four main phases based on the methodology framework of ST theory. The research methodology (Chapter 4) explains in detail the four phases and how the sub-questions are associated with each phase. The main research question and the sub-questions answered through this report is as follows:

"How can the systems thinking approach be used to develop a digital platform ecosystem for facilitating the design of new buildings with recoverable building components from existing buildings?"

- SQ1: What are the barriers responsible for restraining the reuse of recoverable building components from existing buildings?
- SQ2: What are the key drivers of change affecting the design process of building projects involving the reuse of recoverable elements?
- SQ3: How can a simulated model of the 'Building Reuse' system be developed using a serious gaming approach?
- SQ4: How can a Causal Loop Diagram (Systems Thinking tool) be developed to synthesize the fundamental guiding principles of the desired digital platform ecosystem based on the results from the game?

Chapter 3

Theoretical Background

3 Theoretical background of Systems Thinking

The concept of Systems Thinking is the underlying theory driving this research. Before understanding the application of ST in the context of reuse, it is first essential to establish the meaning of the theory, the related concepts and the existing association of the theory to the problem at hand. This chapter first analyses the theory of ST in itself, followed by a short literature review of its association with the built environment and digital transformation. Finally, these three domains are combined to establish the underpinning theory of this research.

3.1 Systems Thinking theory

The concept of 'Systems Thinking' is not new. It originated in the year 1956 from the Sloan School of Management at MIT when the Systems Dynamic Group was created by Professor Jay W. Forrester (H. Meadows, 2009). The concept of ST has been given multiple definitions over the years. However, most of these definitions draw inspiration from the popular book 'Thinking in Systems', written by Donella H. Meadows who was one of the students of Professor Jay W. Forrester. The book defines systems as (H. Meadows, 2009):

"A system is an interconnected set of elements that is coherently organized in a way that achieves something (function or purpose). It consists of three components mainly: Elements, Interconnection of Elements and Purpose of the System."

According to this theory, complex systems present properties that arise from the interrelation between the system's components and with the environment. Systems thinking in practice encourages us to explore inter-relationships (context and connections), perspectives (each actor has their unique perception of the situation) and boundaries (agreeing on scope, scale and what might constitute an improvement) (Allen Will, n.d.). Scientific approaches usually address problems by breaking them down into smaller pieces and analyzing them individually. While it has great benefits, it also has the great disadvantage of ignoring the relationships among system components; those relationships often dominate systems behaviour (Monat & Gannon, 2015). As this theory promotes the idea of embracing complexity, it has found applications in multiple fields ranging from supply chain management to systems engineering and several socio-technical problems which are complex, layered and highly dynamic. The theory offers a wide variety of tools to apply systems thinking to complex problems. The tool of CLD is used in this research which will be explained in the research methodology (Chapter 4). The following section discusses how the built environment can also be considered as a complex network of systems and why ST can be an interesting way of approaching the issues within it. Several terminologies associated with ST will be used in this report which are enlisted in the (Appendix A).

3.2 Systems Thinking and Built Environment

Although the concept of ST is old, the application of ST in the built environment context is relatively new. The built environment is not an isolated entity. It is connected with the surroundings at multiple scales such as materials, components, buildings, cites and multiple domains such as ecology, economy and social (Habert & Schlüter, 2016). Due to the increasing complexities within the domain of the built environment, focusing on the development of individual products and technologies is not sufficient. Such complex systems have a high probability of failure and negative effects if the dynamic nature between the objectives and outcomes are not taken into consideration while planning (Shrubsole, 2018). Majority of the papers connecting systems thinking and built environment deal with its application in the context of energy consumption and urban planning. The concept of ST has been used in the context of the built environment for defining the urban metabolism of a city (Gorgolewski, 2019). It is employed to understand the flows of resources within a city and also, analyse the interrelations between environmental, sociological and economic factors responsible for the resource flows. The Sustainable Built Environment (SBE) Regional Conference in Zurich (2016) published its proceedings in the conference paper 'Expanding Boundaries: Systems Thinking in the Built Environment' (Habert & Schlüter, 2016). This paper has given special emphasis on the use of systems thinking approach in the life-cycle assessment of building stocks and renovation & retrofitting techniques. However, the application of systems thinking concerning the high-level reuse of building components has not been discussed widely.

In the recent past, Systems thinking has received considerable traction in the domain of circular economy. The Ellen MacArthur Foundation, responsible for developing and promoting the idea of the circular economy has established the relevance of ST approach in their article - "How to apply Systems Thinking to support a systems change for Circular Economy?". The article suggests that 'systems' and 'systems thinking' are integral to the concept of circular economy (*Systems and the circular economy*, n.d.). Within the context of circular economy, the systems thinking approach has been utilized in designing circular waste management strategies as opposed to traditional linear and fragmented practices (Viva et al., 2020). Undertaking a circular economy approach with systems thinking at its core, results in various economic, environmental, and social benefits in addressing waste problems (Ng et al., 2019). Based on this literature study, it was concluded that systems thinking has found importance in different domains of the built environment. Considering this as the starting point, this research tries to associate the theory with the reuse of recovered building elements in particular.

3.3 Digital Platform Ecosystems

The term 'Digital Platform Ecosystem' can be fundamentally seen as a combination of two different ideas - 'Digital Platforms' and 'Business Ecosystems'. Before delving into the idea of why DPE is being adopted as a solution to the problem under discussion, it is first essential to focus on the conceptualisation of the term in itself. When it comes to the concept of 'Digital Platforms', there are multiple definitions available in the literature. Some define digital platforms from a technical perspective considering it as a software or tool or a product. On the other hand, some others define these from a non-technical perspective where it is considered as a commercial network of business exchanges. For the purpose of this research, digital platforms can be seen from a non-technical view point as a "digital tool facilitating interaction between two or more mutually interdependent groups of customers" (Ye et al. (2012), Asadullah et al. (2018)). The term 'business ecosystems' was first introduced in the mid 1990s and can be defined as network of organizations that are formed around a central innovation, technology or company with the purpose of creating and delivering products and services (Yiling et al., 2019). Combining these two concepts. DPE can be seen as an ecosystem emerging around a focal platform that provides a combination of hardware,software, infrastructure, organizational and social rules that connects actors around the platform (Gawer & Cusumano (2014), Yiling et al. (2019)). Few prominent examples of DPE include social media platforms such as Facebook, LinkedIN and service-oriented platforms such as Uber, Airbnb, etc.

The construction sector in Europe is slowly undergoing a digital transformation by taking advantage of technologies such as Building Informational Modelling (BIM), automated fabrication (pre-fabrication) using robots and 3D printing, drones, 3D scanning, sensors and Internet of things (IoT) (European Commission, 2019). Taking advantage of the IoT, another emerging concept that ameliorates the usefulness of such technologies is the digital platform ecosystem. The basic idea behind DPE is to combine and deploy these technologies in new ways to incubate and coordinate an ecosystem of supply and demand (Hein et al., 2019). In section 2.3 of Chapter 2, it has been discussed that the inability to enhance the reuse of building components is because of the mismatch in demand and supply at large. In digital platform ecosystems, businesses make use of digital technologies to connect the suppliers and users and thus, facilitate the exchange of goods and services through networking. This concept has been widely used in other sectors of the economy such as ride-sharing, mobile phone apps, social networking, etc. (Sawhney & Odeh, 2020). When it comes to platform ecosystems in the construction industry, it was found that platform thinking is currently restricted to the creation of technical tools (Chan et al., n.d.). This can again be traced back to the lack of ST approach which ignores the inter-relations of socio-economic factors surrounding the platform thinking. The digital platform ecosystem is not oblivious to the concept of ST and is established as one of the fundamental theories supporting platform thinking. By embracing ST, the construction industry has the potential to grow into a thriving platform economy that can benefit multiple areas of the industry, including reuse.

3.4 Theoretical Foundation

In the analysis of problem context, it was established that the reuse of recoverable building elements in new building projects is a complex problem with several layers and multiple dimensions. Thus, a need to establish a system was emphasized to address this issue at large. By containing this problem in a 'system', the theory of systems thinking can be effectively applied to critically analyze the issue and propose a holistic solution. In the above section, it can be seen that the built environment is moving towards complete digital transformation. Utilizing the power of digital technologies is essential for effective and fast-paced attainment of the goals in the circular economy. This research tries to bring together these three different schools of thoughts - 'Systems Thinking', 'Digital Platform Ecosystem' and 'Reuse' (Figure 6) to propose a holistic and well-founded solution to solve the problem of reusing recoverable building elements.

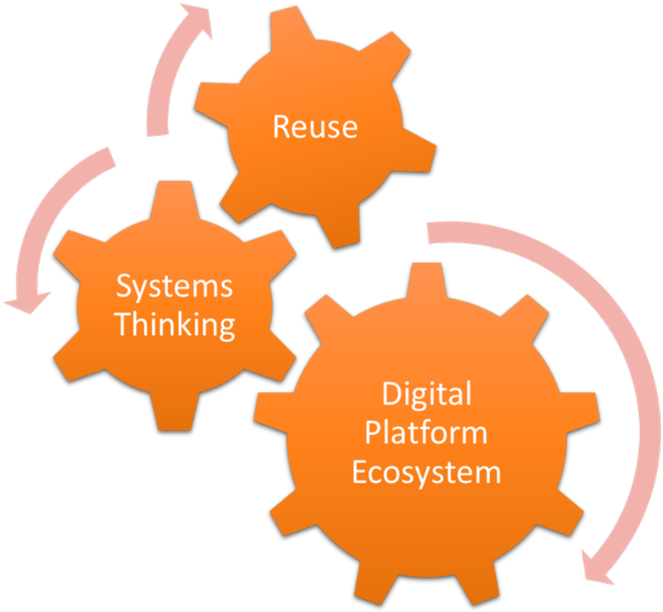

Figure 6: Theoretical Foundation

3.5 Building Reuse System

To clearly understand the scope of this research, it is essential to define the boundaries of the system, its function and essential components based on the complexity of the problem to be addressed. As this research is focused on enhancing the reuse of recoverable building components, the system is named as 'Building Reuse System'. Based on the discussion in problem context analysis, the system needs to connect the two sides of the industry - the supply and the demand. In this case, the supply industry is comprised of the demolition industry responsible for supplying recovered building elements. On the other hand, the demand industry is concerned with consuming the recovered building elements in their project. The 'Building Reuse System' is thus, considered as one whole system which is comprised of two sub-systems namely; 'Building Deconstruction Management System' for existing old buildings and 'Building Design Management System' for new buildings as shown in figure 7. Each system is characterized by a set of elements consisting of actors, processes and values. The two sub-systems are connected through their elements at multiple levels. The system and the sub-systems are defined as follows:

The characteristic features of the 'Building Reuse System' are as follows:

- **Building Deconstruction Management System**: Existing old buildings which are nearing the end of life cycle and are subjected to demolition fits within the system. The term 'Deconstruction' is used to stress that the buildings shall be demolished to recover maximum reusable components.
- **Building Design Management System**: New building projects which have the aim of integrating maximum recovered components in their design fits within this system. It is significant to note that this system is restricted to the 'Design phase' of a building project considering the scope of the study.
- **Building Reuse System**: The overall system is assumed to represent a single project in which reusable components are recovered from old buildings and are integrated into new construction projects.
- **Functional purpose:** The functional purpose of a Building Reuse system is to ensure that a reusable building element (product, material, component, etc.) are efficiently recovered at the end of a building life cycle to be integrated into a new building such that the value of the element is not downgraded.

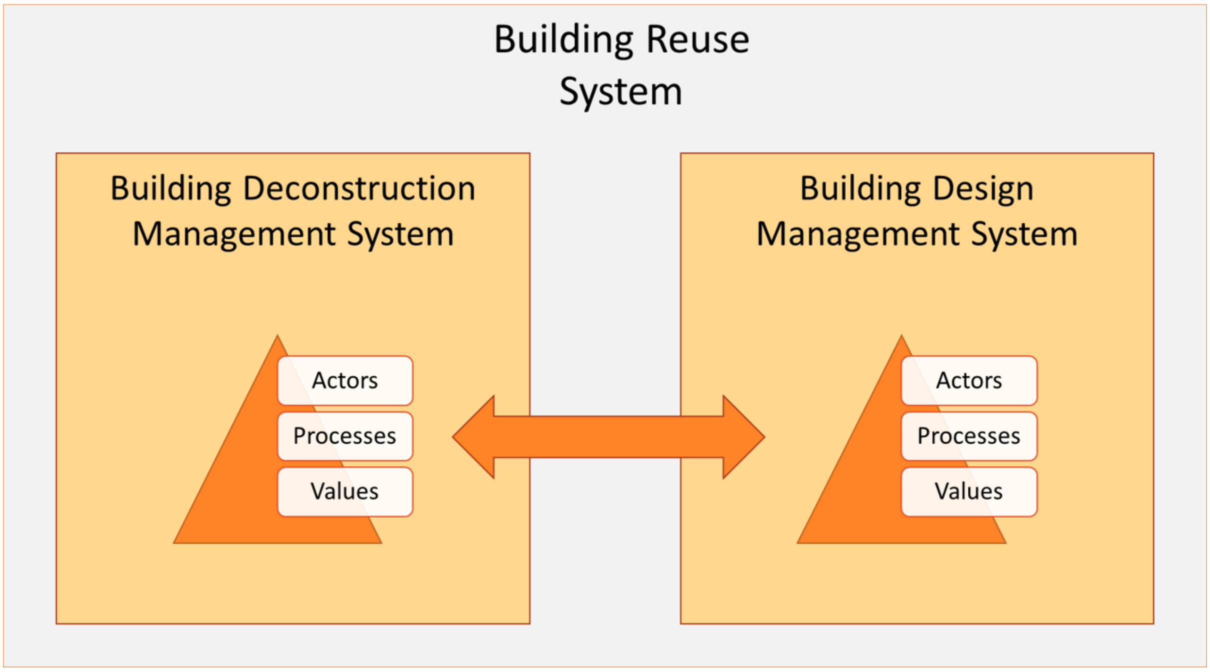

Figure 7: Building Reuse System (own illustration)

- **Open System:** The definition of open system states that "any system that regularly exchanges feedback with its external environment, analyze feedback, adjust internal systems as needed to achieve the system's goals, and then transmit necessary information back out to the environment can be regarded as open systems" (*What Is an Open System?*, n.d.). The Building Reuse system cannot be considered as an isolated system as the life cycle of a building element starts from the initial stage of being a raw material until the end of life when it can no longer serve the desired function. This timeline cannot be restricted to a closed system of reuse. However, the system boundaries, in this case, is defined taking into consideration the scope of this research.

- **Actors:** The actors within the system consist of all the internal and external stakeholders who participate through the entire journey of a product, component, material or entire building right from the moment it enters the demolition phase and is integrated into another project.

- **Processes:** As the name suggests, the processes comprise all the associated activities within the system that help it to achieve the desired functional purpose.

- **Values:** Values of a system are the principles or standards that regulate the system through the exchange of knowledge or information amongst the actors and the processes.

3.6 Building Deconstruction Management System

The traditional demolition processes have been adapted over time to accommodate the principles of circular economy and is now widely known as 'deconstruction'. The processes involved within the system of building deconstruction management are described in several studies and can be broadly classified as shown in the figure 8. The set of processes used in this study are based on the results of (Michael Polina, 2018) and confirmed with the publications of 'International Council for Research and Innovation in Building and Construction' (CIB) ((Macozoma, 2001), (Rinker Sr, 2005), (Kibert et al., 2000)).

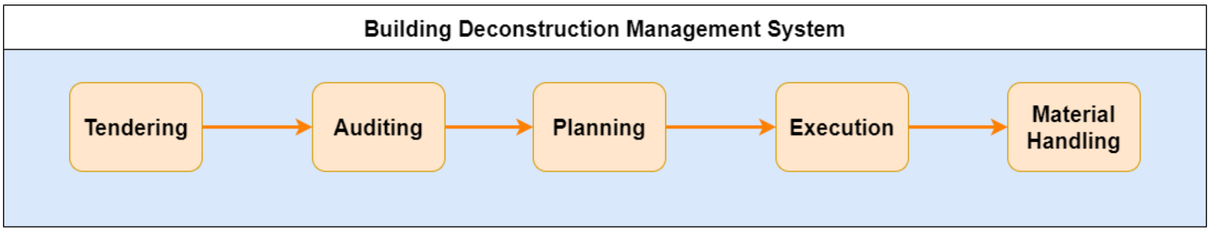

Figure 8: Building Deconstruction Management System (own illustration)

3.7 Building Design Management System

The literature study revealed that the knowledge on how existing design practices can be adapted to enhance the reuse of recovered components in new designs is fairly limited. Examples of a few unique projects can be found in certain scientific papers. However, the methodology adopted in each of the project is different and largely varied based on the characteristics of the project. A generalized methodology to define such design practices has not been developed yet. Thus, the widely accepted stages in the design phase of constructing projects based on the publications of 'American Institute of Architects' (*Design to Construction | AIA ETN*, n.d.) are used in this system as shown in figure 9.

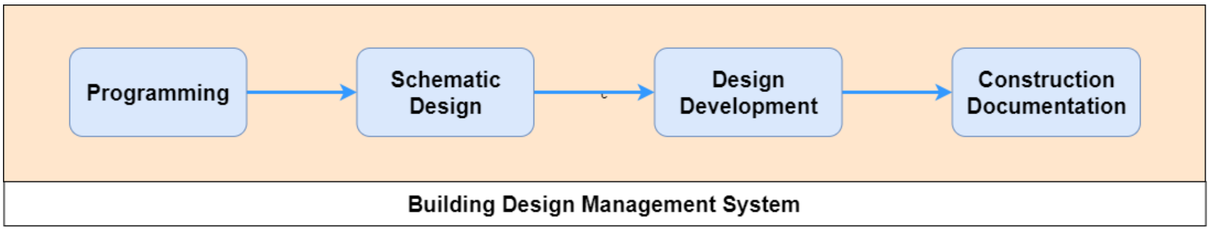

Figure 9: Building Design Management System (own illustration)

A description of these processes involved within the sub-systems is given in Appendix B.

Chapter 4

Research Methodology

4 Research Methodology

This chapter discusses the research approach and associated methods adopted to solve the main research question. The problem under consideration for this study is characterized by its uniqueness and complexity. As a result, the study makes use of multiple research methods for solving each of the sub-question. It begins with explaining the basic framework adopted to apply the ST approach to this study. Each phase within this framework has multiple steps and have unique data collection methods. The chapter concludes with a short overview of the thesis outline.

4.1 Research Approach

The previous chapter on the theoretical background of ST had explained the relevance of the theory within the context of this research. This section focuses on devising the conceptual and analytical method used to apply the ST approach judicially. According to Cavana & Maani (2000), the systems thinking and modelling approach involves five major phases as given below:

- Problem Structuring
- Causal Loop modelling
- Dynamic modelling
- Scenario planning & modelling
- Implementation & organizational learning

Each phase consists of several steps which are summarized in the table 8 given in the Appendix. However, the theory emphasizes that it does not require all the phases to be undertaken, nor does each phase require all the steps listed (Cavana & Maani, 2000). These steps and the phases must be looked at as guidelines. Depending upon the type of problem, the behaviour of the systems and the degree of effort that the researcher is prepared to commit, the framework can be adapted. The adapted methodological framework for the application of ST approach in this study is as given in figure 10 below.

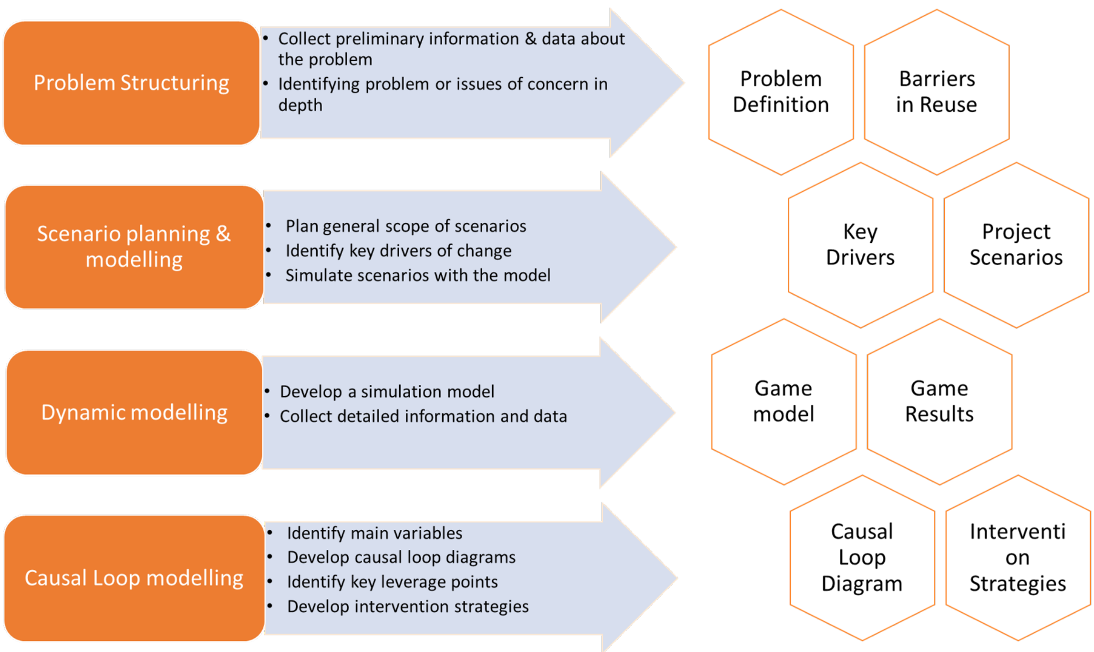

Figure 10: Systems Thinking - Research framework

As compared to the original framework, the last phase of ST approach, Implementation & organizational learning, has been omitted in the adapted research framework. This phase deals with the experimental implementation of the solutions in a microworld (Cavana & Maani, 2000). Microworlds are intended to provide an integral friendly interface to experiment with the developed solutions. These can take the form of learning labs, prototype models or focus group experiments. This phase is proposed as a future recommendation of this research and is elaborated in Chapter 12. The following sections of this chapter explain in detail the different phases of the adapted research framework with a clear motivation for the decision choices.

4.1.1 Phase 1: Problem Structuring

In this phase, the problem under consideration is analyzed and the scope and boundaries of the study are defined. This is a common step in any problem-solving approach and has already been discussed in detail in Chapter 2. Following this, comprehensive desk research was conducted to summarize the barriers specific to the use of recovered building elements. The search primarily covered scientific papers, reports and books available within Scopus, Google Scholar and TU Delft repository. In addition, conference papers specific to the current state of the art programs and technologies as discussed in section 2.2 of Chapter 2 were given special attention. The keywords that were primarily used for conducting the literature study and the keywords for extended search are listed in the table 1 given below. This phase is demonstrated through sub-question 1 (SQ1).

Keywords	**Extended search**
Circular Economy	Reuse, Recycle, Material recovery, Digital solutions, Systems Thinking
Existing buildings as Material banks	Urban mining, Waste management, Demolition
Reuse of Building Components	Deconstruction, Design for Deconstruction, Resource recovery
Material passports	Material and Components bank, Building Information modelling, BAMB, Madaster

Table 1: Keywords - Desk research on Barriers in Reuse

4.1.2 Phase 2: Scenario planning & modelling

Phase 1 helped in understanding the barriers as to why the integration of recoverable components from old buildings in new construction projects is not becoming a conventional practice. In Phase 2, experts from the industry were approached to understand how these barriers were perceived by them. Interviews were conducted with four experts from the Dutch Construction industry. These experts comprised of representatives from the building demolition industry and the building construction industry. One expert each was approached based on their profiles namely, Demolition Contractor, Circularity expert, Structural Engineer and Architect. The details of the demolition contractor were acquired from the VERAS website. VERAS is the industry association for demolition contractors with over 100 demolition contractors as its members (*Leden / VERAS bouwt aan slopen.*, n.d.). The remaining three experts were from Witteveen + Bos organization, representing different expertise. The details of the interviewees are given in the table 2 below. This phase is demonstrated through sub-question 2 (SQ2).

Company Name	**Interviewee Notation**	**Functional Role within the Company**	**Expertise**	**Industry**
G. P. Groot B. V.	Interviewee A	Senior Project Leader	Deconstruction for Reuse	Building Demolition
Witteveen + Bos	Interviewee B	Project Engineer	Circularity	Building Construction
Witteveen + Bos	Interviewee C	Manager Digital Construction	Structural Engineering	Building Construction
Witteveen + Bos	Interviewee D	Senior Architect	Architecture	Building Construction

Table 2: List of Interviewees.

Background of Interviewees

Interviewee A: The company is mainly involved in the deconstruction of residential building projects in addition to a few factory buildings and industrial halls. They have their online marketplace for the sale of salvaged building components and materials. The buyers of their salvaged elements mostly comprise small to medium-sized companies along with some private contractors.

Interviewee B: Interviewee has three years of work experience in dealing with building physics and installations of new and refurbished building projects. In addition, the interviewee also has experience in building projects dealing with circularity.

Interviewee C: Interviewee has about three decades of experience working as a structural design engineer with a wide range of projects and has expertise in the domain of digital construction.

Interviewee D: Interviewee D is a Senior Architect with the first-hand experience in working on a project where attaining circularity was the primary objective. This project had an emphasis on replacing *certain building elements of the project with old salvaged components.*

The interview was mainly conducted to understand the requirements, expectations and preferences of the stakeholders who represent the actors of the Building Reuse system. The results from this interview were used to collate the key drivers and the corresponding project scenarios to be taken into consideration while developing a game simulation model for next phase. The key drivers and project scenarios were integrated with the game elements to provide the players with a 'feel' of working on real projects. A semi-structured interview was conducted with each of the interviewees. The questions to the interviewees largely differed as each of them had a unique background and represented different profiles within the construction industry. However, the questions were broadly classified into two main categories; 1) Perceived barriers in implementing the reuse of recoverable components from existing buildings 2) Probable solutions or expectations to overcome these barriers. The results of these interviews are summarized in chapter 6.

4.1.3 Phase 3: Dynamic modelling

The third phase of the framework deals with developing a simulated environment of the system under discussion. The simulated environment is designed in such a way that the necessary data for the next phase such as key variables, leverage points and intervention strategies are generated through it. It has been well established in the problem context chapter that using recovered building elements in new building projects is an emerging concept. Consequently, the number of projects adopting a reuse strategy is restricted to the use of specific components or materials. Since this research aims to enhance the reuse of building elements to a larger scale, acquiring information based on past learning and experiences was impractical for achieving the research objectives. An alternative data collection method, as opposed to the conventional expert interviews, was deemed essential for this research. A serious research game was developed for this study to create a simulated environment closely reflecting the 'Building Reuse System'. This phase is demonstrated through sub-question 3 (SQ3).

The concept of serious gaming has been given multiple definitions based on the inferences from the literature study and industrial experiences. The most common definition of serious games is *"games that do not have entertainment, enjoyment, or fun as their primary purpose"* (Michael, 2005). The primary goal of a serious game is usually to educate and learn through play (Crookall, 2010). Training and simulation games might represent the biggest and economically most relevant application area for serious games (Göbel, 2016). For this research, the definition given by Susi & Johannesson (2007) is used which states that a serious game is designed to focus on problem-solving, learning elements, working with assumptions to make a usable simulation, and employing communication that reflects real-life situations. Out of the multiple design philosophies that support the development of the serious game, the 'Triadic Game Design' philosophy was adopted for this research. Considering that the researcher has limited knowledge and expertise in the domain of serious game, an expert from 'TU Delft - Game Lab' was consulted during the design process to arrive at the design philosophy.

Triadic Game Design: According to Triadic Game Design (TGD), designing a game revolves around three worlds - 'Reality', 'Meaning' and 'Play' (Harteveld, 2011) and each world is inhabited by different people, disciplines, aspects and criteria as can be seen in figure 11. The design space placed at the centre of the diagram implies that the design problems can be related to each of the worlds because designing is mostly about solving tensions within and between the worlds that inhabit the design space. A good game is a result of striking a balance among the three worlds in such a way that they support one another to achieve the serious purpose of the game. However, the theory insists this approach must be seen as a design philosophy and not a definite structured way of detailed steps that the designer should take. Chapter 7 describes in detail the steps undertaken during the development of the game and the corresponding design principles based on the theory of TGD. It needs to be emphasized here that the game was designed as an online board game. This research was conducted during the lockdown period as a consequence of the Covid-19 pandemic. Hence, conducting a game session with the physical presence of the experts was not possible.

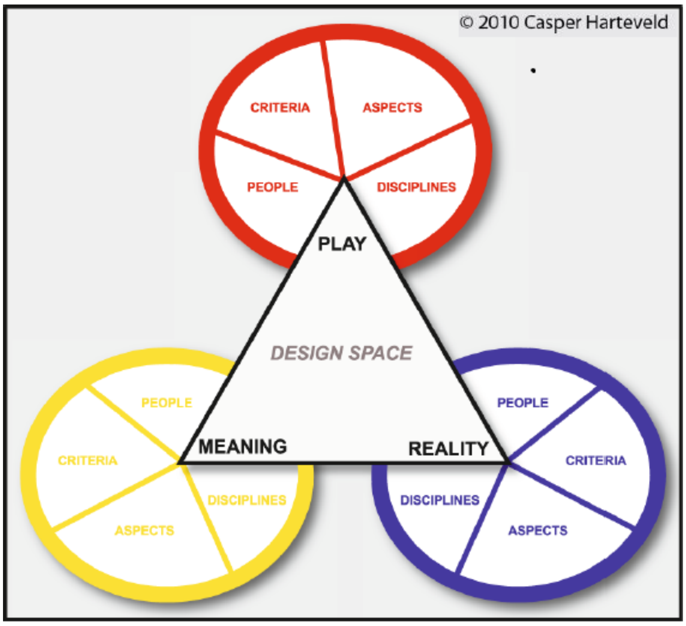

Figure 11: Triadic Game Design
(Reprinted from "Foundations", by Harteveld Casper, Triadic Game Design - Balancing Reality, Meaning and Play (p.34), (Harteveld, 2011))

Data Gathering: The gameplay session was intended to produce qualitative data through data observation and focused group discussion. This qualitative data is then analyzed to generate key variables, leverage points and intervention strategies to be used as input for the next phase of the research. The gameplay was organized in two different sessions. The first session was conducted as an 'alpha test' to evaluate the quality of the game and player experience. The players chosen for this session was a group of three students with an academic background in Construction Management and Project Management. Based on this session, the game structure and elements were improved to suit the research context and 'playability'. The second session was played with experts from the industry. These experts were acquaintances of the researcher from Witteveen+Bos who were also interviewed during the 'Scenario planning & modelling' phase. These players represented the design team of the 'Energy & Architecture' department of the company. The background of these players and their corresponding role in the game session are as given in the table 3. As mentioned before, the game session was held online and the session was transcribed immediately to produce the data. The responses of the team player data was analyzed using content and thematic analysis techniques such as Coding. It is the process of labelling and organizing the qualitative data to identify themes and relationships between them. Predefined codes based on the inputs from the 'Scenario planning & modelling' phase were used to guide the researcher in identifying variables and inter-dependencies. Chapter 7 demonstrates the synthesis of results in detail.

Functional Role within the Company	Expertise	Role in the Game
Manager Digital Construction	Structural Engineering	Structural Engineer
Group Head - Architecture	Architecture	Architect
Project Engineer	Circularity/ Life cycle Assessment	Life cycle analyst
Team Lead - Energy & Architecture	Architecture and BIM	Client

Table 3: Team Composition

4.1.4 Phase 4: Causal Loop modelling

The final phase of the framework is focused on developing a CLD to visualize the interdependencies and interconnections amongst the elements of the Building Reuse system. The CLD is then critically analyzed to identify the possible intervention strategies that can act as the fundamental guiding principles while developing a digital platform ecosystem. The ST approach offers multiple tools and techniques that can be used to analyze complex systems. CLD is one of the basic and most common tools used to develop an understanding of systemic behaviour. Considering the complexities and inter-dependencies of the Building Reuse system, it can be inferred that the relationships amongst different elements are non-linear and non-unique. The elements within a system are affected by multiple dynamic factors and several variables are used to represent these dynamic factors while developing the CLD. To propose an effective solution, it is essential to have a good understanding of the behavioural impacts caused due to change in the variables. Working with CLD offers a holistic view of the entire system, its variables and the cause and effect pattern. Although the CLD can be assumed to be a mere visualization tool at first, these diagrams have the potential to reveal the underlying dynamics of a complex system. This phase is demonstrated through sub-question 4 (SQ4). Before delving into how CLD was applied to this research, it is essential to understand their characteristic features which are explained below.

Causal Loop Diagramming: CLD are tools used to map out the structure of a system to understand how behaviour has been manifesting itself in a system so we can develop strategies to work with or counteract the behaviour (Haraldsson, 2004). The basic logic behind these diagrams is demonstrating the causalities between two variables. This can be explained better by the 'population' CLD, one of the most popular examples used to explain the logic as given in figure 12 below. In this figure, the variable population increases because of the increase in birth rate which in turn increases due to the increase in population. The plus sign is used to indicate that the variables are increasing (decreasing) in the same direction. This type of loop which shows an escalating effect due to the equivalent influences between the components (Haraldsson, 2004) is called the 'Reinforcing loop'. On the other hand, the variable population decreases when there is an increase in the death rate. This inverse relation is showed using the minus sign. However, the increase in population leads to an increase in the death rate which is indicated using the plus sign. This type of loop which hampers the exponential growth or is a limiting factor to the growth of the loop (Haraldsson, 2004) by balancing the variables is called 'Balancing loop'. By critically analyzing these loops, the points of leverage can be identified which can be improved through intervention strategies. According to Donella Meadows (H. Meadows, 2009), "leverage points are places in a system where a fine tune, strategic intervention is capable of creating lasting change, creating positive ripple effects that spread far and wide." The intervention strategies corresponding to the loops thus can be the driving principles towards solving the complexity and barriers of the system.

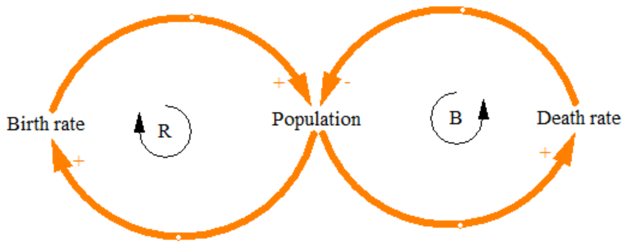

Figure 12: Population CLD (own illustration, based on (Sterman, 2014))

CLD for Building Reuse system: With this understanding of how a CLD is developed as given above, the CLD representing the whole Building Reuse system was developed using the 'Vensim' software. The gameplay session from the previous phase resulted in the generation of multiple key variables affecting the elements of the system. These variables were mapped to get a holistic view of the system showcasing their relations. The codes and themes from the game simulation model were used as a reference to identify the patterns. The final CLD was developed through multiple series of iterations by reverse tracking the cause of each variable. Each loop within the CLD was then critically analyzed resulting in the identification of multiple leverage points. These leverage points were considered as the key driving factors to decide the intervention strategies. The interventions strategies represented the fundamental guiding principles while developing a digital platform ecosystem to enhance the reuse of building elements. Besides, the diagram also revealed multiple balancing loops which, if not monitored, can eventually lead to the collapse of the platform ecosystem. Chapter 8 explains in detail the process of arriving at the fundamental guiding principles from the CLD.

4.2 Thesis Outline

The chapter thus explains the systematic approach used to demonstrate the application of systems thinking theory to develop digital platform ecosystems for building reuse. A summary of the research framework along with the data collection methods, sub-questions and expected outcome is given in figure 13 below:

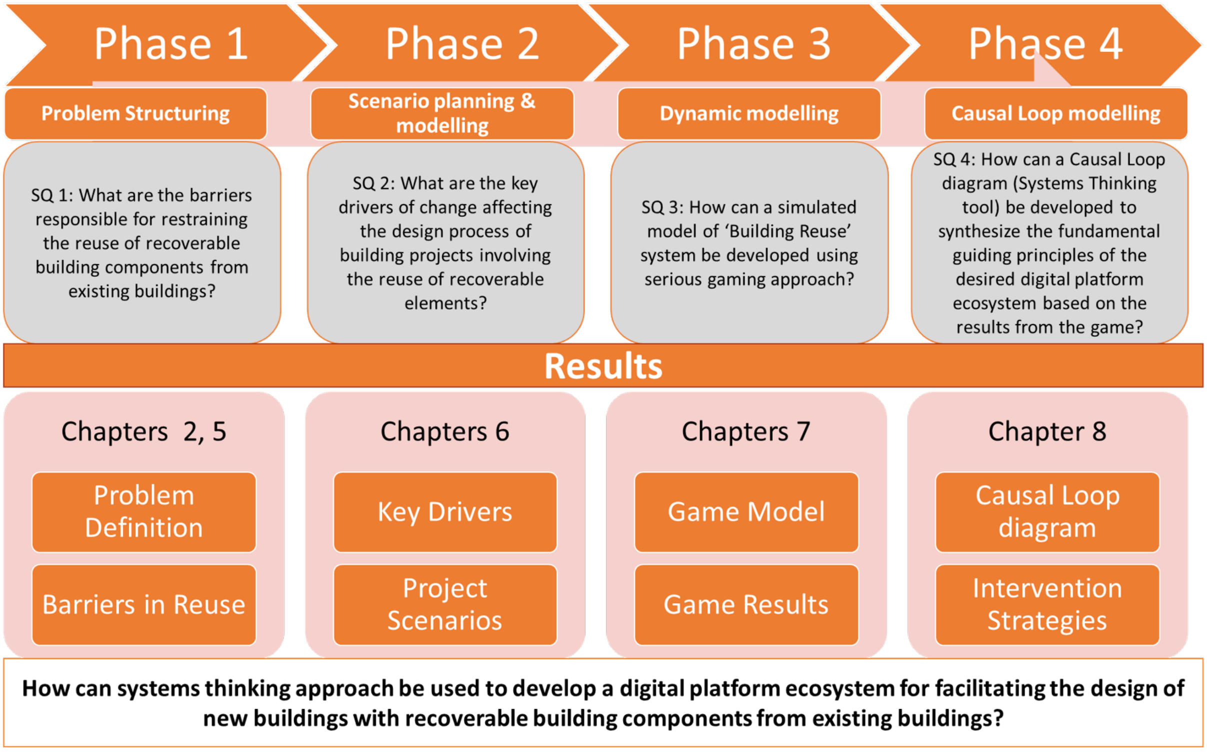

Figure 13: Thesis Outline

Chapter 5

Barriers in Reuse

5 Barriers in Reuse

This chapter corresponds to the first phase of the research framework - 'Problem Structuring'. While the problem definition has already been covered in Chapter 2, this chapter is intended to answer the first sub-question within this phase. The reuse of recovered building elements in new projects has still not become a conventional practice because of a wide variety of reasons. There are extensive literature studies available discussing the barriers obstructing the implementation of circular economy and reuse in particular. From Chapter 2, it is evident that the problem at hand has multiple dimensions. Consequently, the barriers related to reuse needs to be studied from different perspectives such as economic, technical, regulatory, environmental & safety, organizational and social. The author of the report does not claim the following barriers to be exhaustive and complete. However, most of the barriers obtained from the extensive literature study are summarized here and they act as the starting point towards the analysis.

5.1 Economic barriers

According to Rakhshan et al. (2020), 'cost' is the most reported category in the list of reuse barriers. These costs are mainly due to the additional time and efforts required to deconstruct a building against conventional demolition (Hobbs & Adams BRE, 2017). Besides, additional costs are incurred in the deconstruction process because of lack of equipment, unavailability of storage space, complex building designs (Tatiya et al., 2018), transportation costs (Yeung et al., 2015) and fabrication costs (Tingley & Davison, 2011). A disparity between the location of stocks and the market of such reusable elements concerning space can add to the risk of using reusable elements (Hobbs & Adams BRE, 2017). On the other hand, the design company involved in integrating recovered element also has to bear extra costs due to flexible designs and additional human resources in the design team. These eventually lead to cash flow problems and increase the overall cost of projects (Rakhshan et al., 2020).

Several attempts to establish a well-functioning market by multiple demolition companies are often met with failures because of the mismatch in demand and supply. The mismatch is not only in terms of quantity but also in terms of quality (Hobbs & Adams BRE, 2017). Demolition contractors or vendors, responsible for supply, do not invest efforts in the retrieval of reusable elements from existing buildings because of the lack of demand from the client/architect side. On the other hand, the adaptations in the traditional design processes based on the available material quality, dimensions and other specifications along with their time of availability and purchase adds to the complexities. The lack of demand can also be attributed to the tight project schedules both on the deconstruction side and the building construction side (Tatiya et al., 2018). The majority of the recoverable elements, thus, end up being sent to recycling processes due to the uncertainty in their applications (Dunant et al., 2018). As a result of the underdeveloped market and the fragmented supply chain, the reuse rate of building elements further decreases (Rakhshan et al., 2020).

5.2 Technical barriers

Although certain initiatives are being taken in the construction industry to design new buildings which can be disassembled in the future, the buildings constructed in the earlier days cannot be easily deconstructed. The building information and structural drawings are often not available which makes it difficult for the contractors for efficient recovery. In addition, the use of composite materials, permanent connections, presence of hazardous materials (eg. asbestos) contribute to the complexities (Densley Tingley et al., 2017). While analyzing the technical feasibility concerning deconstruction, the difficulties concerning designing with recovered components must not be overlooked. The inherent flexibility in the design is essential to be able to incorporate alternative dimensions based on the availability of the desired components (Gorgolewski, 2008). There is usually an urgency to complete the projects as early as possible (Chinda & Ammarapala, 2016) which restricts the opportunities for efficient disassembly of existing buildings and the chance to integrate them in new construction projects (Sansom & Avery, 2014). The geometry of a building structure will be largely dictated by the available components. In addition, the uncertainties with the remaining structural capacities of the components, their quality, durability, health and safety concerns and environmental impacts add to the technical difficulties (Rakhshan et al., 2020).

5.3 Regulatory barriers

Governmental policies play a major role in enforcing the use of recovered elements and regulating the circular economy. Quality and performance take precedence when dealing with, especially the structural components (Hobbs & Adams BRE, 2017). Currently, there are no exclusive regulations that encourage the reuse of elements in the European construction industry (Rameezdeen et al., 2016). No standards are regulating the compliance of such elements with health and safety regulations. The reusable components cannot be validated currently for performance requirements through standard quality certificates (Dunant et al., 2018). This eventually leads to the lack of confidence in the component and has a negative impact on reuse (Ajayi et al., 2015). In addition, the government is providing no incentives to the stakeholders who take such initiatives. This discourages the demolition contractors to take a risk in investing the additional time and money for deconstruction as opposed to demolition. Another implication of the absence of a regulatory framework is that the demolition contractors are often ignorant about the difference in retrieving elements for reuse and recycle. The reusable components are often sent to the recycling stations without an opportunity to explore the potential for reuse.

5.4 Environmental and Safety barriers

The uncertainty in the environmental and safety implications accompanying the reuse of materials and components is one of the major factors for creating a negative perception towards them. The existing technologies supporting the deconstruction activities are not sufficiently developed (Hobbs & Adams BRE, 2017). Resorting to manual labour for careful removal of elements involves high health and safety risks. These risks can be partially overcome with clarity on the structural and non-structural composition of the buildings which is not the case always. In addition, localization of the market through the establishment of recovery facilities is essential to reduce the environmental impacts. If the materials are required to be moved over long distances, it will eventually have a detrimental impact on the environment (Hobbs & Adams BRE, 2017) and thus, rendering the reusable elements less feasible.

5.5 Organizational barrier

The perceived difficulties in incorporating reusable elements into new buildings often discourage the clients and the designers from embracing reuse (Gorgolewski & Morettin, 2009). The lack of skills, experience, and knowledge in deconstruction and reuse negatively affect the establishment of such practices (Hosseini et al., 2015). The literature study revealed that there is a greater emphasis on improving the supply side with methods such as circular demolition and selective deconstruction. Despite the efforts, the demolition contractors are not completely aware of the applications of their retrieved components. It is the need of the hour that stakeholders from the client-side (architects/designers) must intervene in the deconstruction process of existing buildings for the successful integration of recovered components into the design of a new building. "Issues of availability, supply chain, ownership, detailing, codes and standards, acceptability, and availability of information may all impact the design and delivery process" (Gorgolewski, 2019). The clients may naturally tend to go for standard products considering the impending challenges. Inequality in the distribution of risk among the stakeholders can still challenge the motivated clients and architects ((Rakhshan et al., 2020), (Dunant et al., 2018)). However, an initiative at an organizational level where design principles are established to maximize the use of recovered components is a significant step. Other organizational barriers include proprietary lock-ins (Densley Tingley et al., 2017), the need for infrastructure and equipment to perform deconstruction (Rameezdeen et al., 2016).

5.6 Social barrier

Stakeholders play a very important role in accelerating the establishment of reuse in the circular economy. The negative perception of the stakeholders towards the usage of such recovered elements is one of the major social barriers (Rameezdeen et al., 2016). The poor visual appearance of the recovered elements can cause be misinterpreted as lower quality when compared to a new element (Rakhshan et al., 2020). The negative perceptions are generally because of the limited awareness amongst the stakeholder regarding the benefits of reuse. As discussed in the environmental barriers, the occupational hazards associated with the process of deconstruction or recovery adds to the limited acceptability of such elements. Trust plays a great role while dealing with such elements currently because of the absence of a standard regulatory framework (Dunant et al., 2018). While the need to bring all the demolition contractors (Supply Industry) is stressed upon, the necessity to include the perspective of designers (Demand Industry) often gets ignored. Designers of new buildings may have to collaborate with demolition contractors to establish the availability and quality of recovered components, a general idea on the scope of projects and specifying the requirements (Gorgolewski & Morettin, 2009). If the client is motivated to use the reused building components, the barriers such as the unwillingness of the design team can be overcome ((Rakhshan et al., 2020), (Dunant et al., 2018)).

Conclusion on the Barriers: The necessity of adopting a holistic approach was recognized in the problem context analysis part of the research. Based on the literature study, it has become evident that the barriers related to reuse have multiple dimensions. This reveals the necessity of approaching the problem from a holistic perspective which is implied through the use of Systems thinking theory. These barriers will be used at a later stage while reflecting on the reliability of the systems thinking approach towards reuse. A summary of all the barriers with the representative keywords is given in figure 14 below.

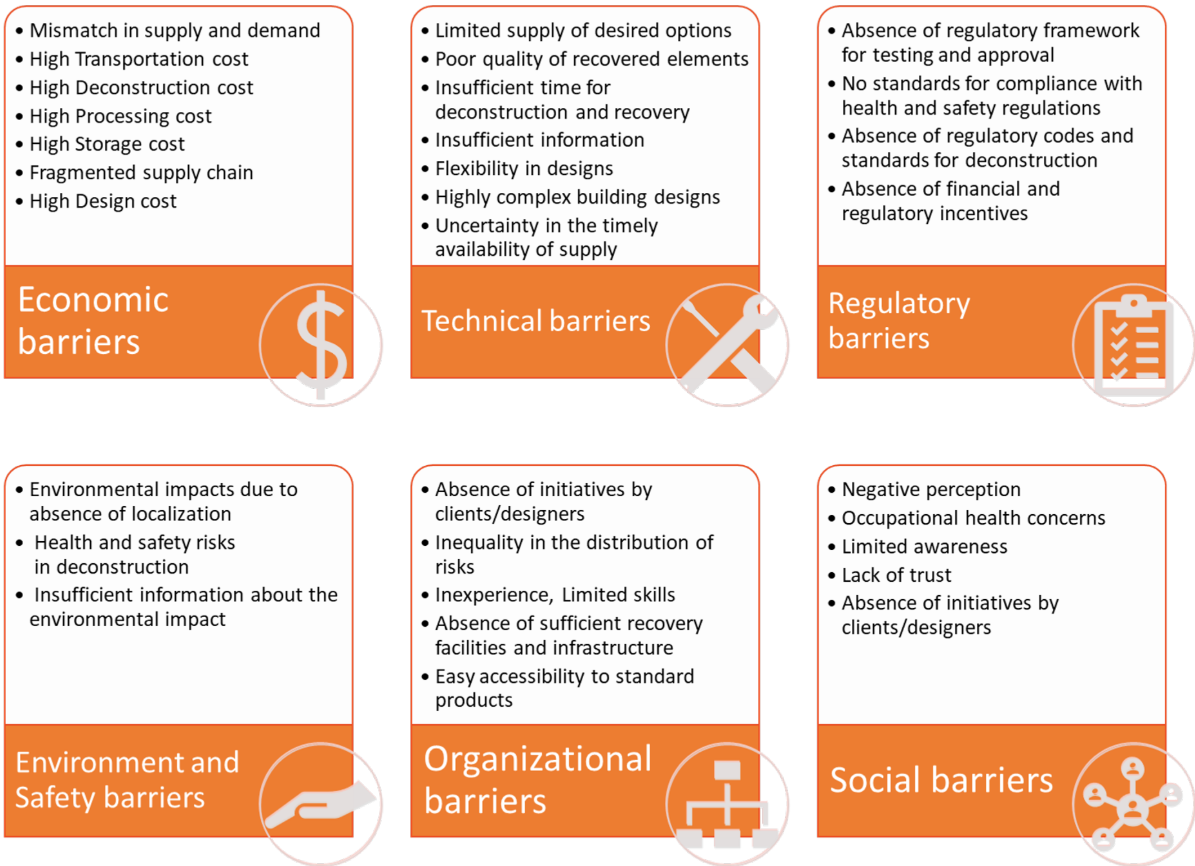

Figure 14: Summary of Barriers in Reuse

Chapter 6
Key Drivers and Project Scenarios

6 Key Drivers and Project Scenarios

The literature study from the previous chapter helped in understanding the barriers as to why the integration of recovered components from existing buildings in new construction projects is not becoming a conventional practice. This chapter corresponds to Phase 2 of the research framework, where the aim is to understand key drivers that facilitate the change in the construction industry to support the reuse strategy. Experts from the industry were approached to understand how these barriers were perceived by them. It has been notably stressed by the scientific literature that involvement and collaboration of stakeholders is an essential step forward to achieve the goals of reusing building elements. Expert interviews were essential to understand the requirements or preferences of the stakeholders involved in the process. These were summarized to identify the key drivers and finally to develop project scenarios as an input for the next phase of the research. These experts comprised of representatives from the building demolition industry and the building construction industry. The methodology adopted in the selection of experts, collection of the primary data and the following analysis is explained in detail in chapter 4.

6.1 Economic Feasibility

Economic feasibility has appeared to be a major concern for either parties as per the literature study. Upon analyzing the insights from the expert interviews, similar conclusions could be made. Interviewee A stated that clients who offer demolition projects are often not willing to invest a lot of money. This restricts the demolition contractors to explore the potential of old buildings to offer reusable elements. Besides, deconstruction of old buildings is an intense process as a result of the permanent joints, presence of hazardous materials, inaccessible parts, etc. Thus, the demolition company focuses on retrieved building elements for reuse only if it is economically viable. If the net profit in the sale of reusable elements seem to be negative, these elements are often sent to recycling units. Interviewee B suggested that measuring circularity through reuse should not be restricted as to the economical aspects but should also consider the long-term implication of it. If the element proves to have detrimental impact on the environment in the long run and calls for a replacement, it should be considered as non-feasible. Interviewee D mentioned that a major guiding factor in choosing the right kind of material or component is the cost. The option to use second-hand wooden components as facade of the stated building project was dropped as it would have required a lot of maintenance work. The client expressed reluctance in investing in such a long-term maintenance. In addition, it was also observed that the client expressed hesitance in acquiring reusable elements from distant places as it will affect the time and cost of the project.

6.2 Role of Clients and Designers

One of the prominent outlook by all the stakeholders equally was that there is a lack of initiative from the client and design side. Interviewee A pointed out that demolition contractors play a relatively small role in enhancing the reuse of old building components. Interviewee A suggested that architects have to be willing to be flexible with their designs. It is currently not possible to provide building components to match their exact requirements which is making the sale of such products difficult. On a positive note, Interviewee D was willing to be flexible with their design, though more options in the market would be desirable. Interviewee C and D particularly expressed enthusiasm in taking up projects where they could explore the possibility of integrating salvaged elements in their designs. But there has to be initiative by the clients and at the organizational level to promote such projects. Interviewee B was of the perspective that the construction industry is generally very conservative and it takes a considerable amount of time to adapt to new practices. Interviewee B expressed challenges such as having to put additional efforts in exploring and integrating salvaged reusable elements making the design less flexible eventually. Interviewee C stated that the technical, organizational, contractual challenges can be overcome eventually if there are potential clients interested in such projects. As mentioned in section 6.1 by Interviewee D, the client was reluctant to invest in maintenance of a second-hand building product which imposed the architect to drop the option. Besides, the hesitance was faced in acquiring salvageable elements from distant places considering the limited time and cost. Thus, the clients should have a positive outlook towards implementing such projects which will encourage the designers/architects to experiment and explore.

6.3 Building Information database

The online repositories such as Madaster and BAMB were known to be the most prominent projects existing in the industry that is focused on enhancing circularity in the market. These projects are known to be initiated with the idea of storing information about the building components and materials which resembles a passport. The intention behind these projects is to collate information about all the buildings on a single platform which can be utilised by multiple stakeholders with an interest in circularity. The interviewees were posed question about their knowledge in using such platforms for serving the purpose of reuse. Interviewee A stated that these platforms mainly seek information in the digital form. Most of the buildings that are being dealt in the demolition industry do not have a digitized model. Spending money to digitize these buildings does not seem to be an economically feasible option. It usually happens that there are no proper documents or drawings of these structures which proves to be an additional effort on the side of demolition contractors. Developing an inventory often becomes difficult for older buildings as many unexpected elements are revealed during the process of demolition. Although Interviewee A strongly believes that these online platforms are very valuable for enabling reuse of buildings in the future, it is not very beneficial to use it for current demolition projects.

Interviewee B and C had similar opinions about these material passports. Although they did not have first-hand experience in using it, they do believe that these platforms are being used for several projects. However, the benefits of storing information for assessing circularity were again stated to be limited to new building projects. Construction companies with an ambition for achieving circularity are taking initiative to maintain records of their buildings using these material passport platforms. No instances of these platforms being used for reuse of old buildings were mentioned in these interviewees. This could be also an implication of the limitation stated by the Interviewee A that developing an inventory for platforms like Madaster and BAMB is an expensive affair. In addition, Interviewee A also pointed out that using Madaster for storing building data was costing addition money which cannot be a viable option considering the uncertainties around the purchase of reusable components. The building inventory data developed before the deconstruction process could be shared with the potential buyers by contacting them directly or through other online markets without having to incur the additional costs of using a platform like Madaster.

6.4 Lack of an established market

The presence of a fragmented market for the sale of reusable components was perceived as one of the reasons for uncertainties in demand by Interviewee A. Interviewee D stated that one of the difficulties that designers face while trying to look for reusable elements is that the information is either scattered or not available. There is a need of having a lot of more options in the market to choose the desired reusable elements. The availability of such limited options currently often pressurizes the architect to reserve what is available. Otherwise, there might arise a need to modify the designs at a later stage adding to the costs and time. Interviewee B suggested the need to have the liberty of discarding a reserved component later if it is adding to the complexity of design. Interviewee C expects the availability of information as clear and precise as 'Lego' blocks in an ideal situation. Interviewee B also used 'Lego' as an example in stating how the information are expected to be present in an ideal world. However, it was stated by multiple interviewees that there is often no sufficient information on the available markets and often the architects have to contact the respective demolition company or the market place. The construction industry is definitely moving towards achieving this objective though it seems to be very futuristic. It was though positively confirmed by all the interviewees that a market can be established only if the new building projects take efforts in integration of used elements in their designs.

6.5 Supply - Demand Industry Intervention

Interviewee A was mainly posed with the question to understand if they have encountered specific requirements from architects interested in reusing salvaged building elements. It was mentioned that they had participated in the 'Cirkelstad' initiative where they could have a dialogue with potential architects and builders on how the circularity goals can be achieved. However at the moment, only 20% of their total network of customers comprised of architects. These architects have approached them with specific requirements before deconstruction and efforts were made to adapt their methods to achieve maximum reuse. The initiative taken by the deconstruction company in this case to digitize reusable elements was quite intriguing. The company invests in developing Building Information Modelling (BIM) models of specific building elements that have the potential for reuse. The objective behind this process is to facilitate the efficient transformation of information to the concerned architect/designer upon request. Digitizing the elements also facilitate the acquiring of structural performance specifications. This example proved to be an interesting point of intervention on how either parties can collaborate to enhance reuse of old building elements.

The suggestion of developing a platform where demolition companies and construction companies for new projects can come together was proposed as a solution to all the interviewees. Interviewee A expressed the goal of developing a network where all the stakeholders involved in a new construction project namely, architects, clients, engineers, installation companies, etc are connected to the demolition company. Interviewee D too expressed the need of having a dialogue with the demolition companies to understand how an element can be reused efficiently which could be done by having a single platform to collaborate. Interviewee B particularly stated the need to have such platforms to develop trust in the building elements being used and how such platforms can help in being proactive. Interviewee B expressed that within the building construction projects, certain disciplines get precedence over the others. Building physics and sustainability is also discipline like circularity which loses importance at some stage of the project either because of costs or complexity. Thus, prioritizing circularity while design projects is very critical.

6.6 Technical Feasibility

All the interviewees were positive about the possibilities of reusing building components from old buildings in new buildings projects. However, there was a rather skepticism with respect to the scale at which this could become practical. Interviewee A involved in the building deconstruction industry confirmed that retrieval and usage of salvaged non-structural components have been tried and tested in the past to attain successful results. These non-structural components manly included the windows, doors, sanitary fittings, roof tiles, floor coverings, etc. Within the structural components category, interviewee A states that there have been a few projects were wooden and steel beams have been recovered for reuse. While on the flip side, Interviewee C and D expressed that it is technically possible to reusable elements in new construction projects. That said, it was confirmed the rate at which such projects happening in the industry is very low. Interviewee C was confident of reusing structural components such as steel beams in two or three storeyed structures. However, using such salvaged components for high-rise buildings needs to be analyzed as safety and complexity takes precedence. Interviewee D, being an architect was more concerned about the aesthetics involved in using old components. Interviewee D has personally been part of a project where an old steel roof canopy was reused. As one of the major requirements of this project was to uphold circularity, a rugged appearance was appreciated. It can however vary depending upon the client's perspective. Given that the aesthetics does not necessarily have to be compromised, reusing old elements in new building projects is welcomed by interviewee D.

With respect to the choice of materials for reuse, Interviewee A has the preference of components made of wood, plastic and concrete. Such components can be reused efficiently and also guarantee a successful business opportunity. However, with respect to concrete, the possibility of reuse was mainly by converting concrete elements to rubble and to be used in pavements. The possibility of reusing concrete for the same function as it served before was not evident. Interviewee C suggested that reused of steel components in new buildings projects is the most feasible option as compared to other materials. With respect to structural steel components, redesign the connections to accommodate the uncertainties for old elements will be the major task. In conclusion, there was a consensus by all the interviewees that the technical feasibility can be explored more only when more projects are implemented in real practice. It could be perceived that it is a continuous learning process and there is a lot of scope for improvement with projects.

6.7 Government Regulatory Framework

Absence of a regulatory framework as a significant barrier has been emphasized through the scientific papers. Interviewee A stated that the government has a huge role to play especially when it comes to pushing the demolition contractors to retrieve elements from old buildings for reuse. The policies of waste diversion from the landfills to reduce the environmental impacts of the CDW have been formulated by the government. This has showcased successful results in the construction industry as well. But there is still ambiguity in how and to what extent building components can be reused efficiently. Interviewee A points that the government should increase the price of new construction materials which will eventually force the architects or clients to resort to using old building components. In addition, the problems faced by demolition contractors with respect to high labour costs and absence of quality certificates to legalize the sale of reusable components were highlighted as well. While considering the other side of the industry, Interviewee C and D mentioned that the absence of standard specifications against which the reusable elements could be verified and certified is a concern. In order for the designers to accept the specified quality of the reusable elements, government should be able to build a framework for their testing and approval.

6.8 Conclusion

The above findings were found significant in understanding the requirements, preferences and expectations of the concerned stakeholders in normalizing the integration of recovered building components in new building projects. A summary of the inferences corresponding to each key driver is listed below. Several project contexts were noted in these interviews which can be translated to game scenarios for the next phase. As it would be more appropriate to explain the development of scenarios in the next chapter, these can be found in section 7.1.2 of the next chapter.

- **Economic Feasibility:** Although the economic feasibility is a major deciding factor currently, several aspects of this barrier can be associated to the demand side of the industry. Demolition contractors are skeptical about investing time, efforts and money in retrieving elements for reuse because of the uncertainty in demand. If initiatives are taken from the demand side of the industry to buy such reusable components upfront, it can solve the barrier of cost to some extent.
- **Role of Clients and Designers:** The need for demolition contractors and architects to collaborate and understand the requirements of both parties cannot be discounted. The demolition contractors do not have sufficient information regarding the requirements of architects. The rate at which architects approach the demolition contractors before the deconstruction process is very limited. Most of the interactions are through online markets in which details are published based on the demolition contractors' expertise and knowledge in material management. If an architect is able to produce a list of the preliminary requirements to the demolition contractors, it can be seen as an opportunity for them (Demolition Contractors) to further explore the potential of reuse of several building components.
- **Building Information database:** The importance of maintaining informational database was recognized and appreciated by all the experts equally. However, the pilot projects running in the industry such as Madaster and BAMB have not been largely accepted yet. There are multiple reasons for this inhibition such as added efforts, cost, popularity, awareness, etc.
- **Lack of an established market:** The fragmented nature of the supply industry in the form of multiple online markets appears to be a significant factor contributing to the communication gap between the supply and demand industry. A centralized database where all the demolition contractors register the information about their building projects will strengthen the link and help in expanding the options available for the demand industry.
- **Supply-Demand Industry Intervention:** The need for the two sides of the industry to collaborate with each other has been significantly stressed by all the experts. In addition, it also important that architects communicate their requirements clearly to the demolition contractors to eventually assist the supply industry in recognizing and adapting to the needs of the demand industry.
- **Technical Feasibility:** Deconstruction of old buildings to effectively retrieve reusable building components is technically challenging. However, it has been acknowledged that these challenges can be overcome eventually with more experience and knowledge acquired by working on such projects. Similarly, architects/designers too can build on their expertise by working in close coordination with demolition contractors.
- **Government Regulatory Framework:** The government does have a significant role to play in regulating the construction industry. These regulations are not only restricted to the standardization of processes involved in reuse, but also concerns the regulation of the supply chain network. Absence of quality testing and approval is one of the key reasons for the non-acceptability of the recovered elements. The supply chain, too, needs regulation and also liberalization at certain points to facilitate the reuse.

Chapter 7

Serious Gaming

7 Serious Gaming

This chapter corresponds to the third phase of the systems thinking framework - 'Dynamic modelling' and answers the SQ4. In the research methodology chapter 4, an overview of the concept of a serious game and the theory of TGD was given. Based on this theory, this chapter explains the development of the game model in three different stages; Meaning, Reality and Play. The game scenarios and elements used in this phase are derived from the project scenarios obtained from the stakeholder interviews of the previous phase. Section 7.1.2 of this chapter discusses the translation of data from stakeholder interviews to the corresponding game elements/scenarios. In section 7.2.1, the responses from the players are analyzed and key variables for the CLD is derived.

7.1 Design and Development of Game

Based on the theory of TGD, the development of 'Building Reuse' game is divided into three main stages: Meaning, Reality and Play as described in the following paragraphs.

7.1.1 Meaning

The main factor that differentiates a normal game from a serious game is the meaning of value-added beyond the game experience. A meaningful effect is created when the players are required to achieve certain objectives which are beyond the goals within the game. It is used to describe the intention behind designing the game and the values derived from the playing experience. These can take the form of learning outcome, decision process or improved understanding of a system. In this study, a simulated model to represent the 'Building Reuse' system was developed. As explained in the introduction, the game was played with the experts in the industry to derive the key variables associated with each game element or scenario. The following paragraphs demonstrate the 'Meaning' of the game based on the TGD approach:

Context: A game design development starts by setting a context and this context has a significant influence in achieving the purpose of the game. The context can be associated with multiple factors such as the target group, the physical setting in which the game is played, mode and the external environment. This research was conducted at a time when the country was under lockdown due to the Covid-19 pandemic. This was one of the major driving factors to develop this game in a completely virtual format. A simple online board game was designed to simulate the conditions of a 'Building Reuse System'. The resources provided by the online platform called 'Flippity.net' was used to design the mainboard and the associated game elements. While playing the game, the players were expected to join a video chat to facilitate focus-group discussions. This game was intended for the experts from the demand side of the industry, in this case, the actors involved in the design process of building projects. Although this game is primarily used in this research for data collection, the game can also be used otherwise with the industry experts to create awareness on the topic.

Purpose: The underlying purpose of this research is the added value of developing an improved understanding of the system. The industry has limited experience in working with projects where recovered elements are integrated at a larger scale. This study attempts to mitigate this gap by creating a simulated environment to represent the project scenarios. The players had to design a fictional building based on the client requirements in such a way that maximum recovered elements are integrated into the project. The team players represented multiple actors taking part in the Design phase of a building project and had to collaboratively work towards achieving the goal. Through the game, the players had the opportunity to think, interact and decide on several scenarios which were developed based on the results from the previous phase. The research aims to collect data from the experts in the form of key variables that emerge during the game. These key variables are nothing, but the causes and effects of specific project scenarios which are derived from the knowledge of the experts. The learning curve of the players is limited as the players are assumed to be experts in the industry and are already familiar with the context of the game. However, the play elements are designed in such a way that creates a sense of immersion to allow the experts to respond adequately to the project scenarios.

7.1.2 Reality

As the name suggests, this stage is used to establish how closely the game can represent reality. The game should be designed in such a way that the results from the game can be easily be traced back to reality. As has been already stated, the game scenarios were developed to represent the multiple project scenarios identified during the expert interviews. The following tables showcase how 'reality' was translated into the game. Table no. 4 showcases the game elements used to simulate the system and table no. 5 showcases all the project scenarios that were integrated into the game as game scenarios.

No.	Reality	Game Element
1	The design phase of a building project is classified into four main stages as described in the processes part of the 'Building Design Management System'.	The 45 squares on the board as shown in the figure 44 is divided into four strips corresponding to the four stages of the design process.
2	Existing buildings nearing the end of the life cycle can be demolished and suitable building components may be recovered.	A fictional building project case is introduced in the game with a brief overview of the building age, geographical location and structural configuration.
3	Several barriers are encountered during the design process of a building project-specific to reuse	An obstacle board is introduced in the game with three obstacles placed during the design process.
4	Designing with integrated elements calls for additional steps in the design process.	The additional steps in the design process are integrated with the game in the form of tasks.
5	The client's approval of deliverables after each stage of the design process is important.	Four checkpoints are introduced at the end of each level where the players are asked to get the approval of Game Master to move forward.
6	Building Shear Layers are used in reality to classify a building (refer figure 43 in appendix)	Building Layer Board (figure 16) is used to represent the Building Shear Layers. The board was used to place tags on each component in the 'building layer board' based on the decisions (tags - new/old/final).
7	At the end of each stage in the design process, the design team is required to submit a set of deliverables to indicate their decision on the choice of recovered elements.	Two tags are provided along with the 'Building Layer' board. The 'old' tag indicates that a particular component in a building layer will be a recovered component. Similarly, the 'new' tag indicates that the component will be a new component made out of raw materials.
8	Several online marketplaces are available that provide multiple options of recovered building elements.	An online marketplace 'https://gebruiktebouwmaterialen.com/' was provided as a resource to explore the available options of recovered building elements.
9	Actors of the 'Building Design Management System'.	The role of the players is defined as 'Architect', 'Structural Engineer', 'Circular Economy consultant' and 'Client'.
10	Clients take the final call on the decisions made in the project and hence need to be present throughout the design phase.	A game master is introduced in the game who has the right to start, stop and divert the game process.

Table 4: Reality Worksheet: Game Elements

No.	Reality	Game Scenario
1	Designing a building project takes place in four stages - from 'programming' to 'construction documentation.'	The players are required to go through four levels, each representing a stage of the design process.
2	The design team may choose to source the reusable elements from a specific building project. This calls for interaction with the processes and actors of the 'Building Deconstruction Management system'.	**Obstacle 1:** The team players are given the option to interact with the researcher to ask for details about the fictional building project.
3	Designing with integrated elements needs a sufficient amount of design flexibility and can lead to multiple iterations. At the end of every stage, a decision must be regarding the choice of materials.	The 'Building Layer' board is provided with a 'final' tag to facilitate the decision process. Assigning the 'final' tag to a particular component indicates that the component is already sent for sourcing. Changing the decision can have implications on the cost of the project.
4	Any project needs to be finished within a reasonable stipulated time.	The gameplay session was restricted to 1.5 hours.
5	At the beginning of the project, it is essential to understand the expectations of the client. Accordingly, the design team should define reuse-specific goals and objectives.	**Measure the Reuse Target (Task 1):** The team players are encouraged to define the criteria upon which the reuse target shall be measured and communicated to all the stakeholders.
6	To compensate for the absence of standard regulations for testing and approval, the design team is encouraged to develop its internal grading and assessment criteria.	**Inspection Time (Task 3):** The players are required to conduct a preliminary inspection of the fictional building project. As part of the inspection, the players are encouraged to develop a checklist for grading and assessment. It was necessary to include the details of the criteria.
7	Currently, the available online marketplaces do not provide sufficient on the available recovered components. The design team needs to collaborate and communicate with the suppliers to retrieve the necessary information.	**Information Request (Task 2):** To provide the players with an opportunity to interact with the suppliers and communicate their requirements, a 'request form' was introduced.
8	At the end of a project, it is essential to review the lessons learnt during the project. The challenges faced and their corresponding solutions are essential for future improvements.	**Functionalities (Task 4):** A set of 4 questions were asked by the Game Master to the team players to understand the difficulties they faced during the process and how these can be improved in practice.
9	The decision on which recovered elements are suitable for the project, multiple factors need to be taken into consideration. This could be possible using life cycle impact assessment.	**Obstacle 2:** To encourage the players to think towards life cycle assessment, the game master introduced an obstacle involving the client's concern about the reliability of the decision choices.
10	Designing with integrated elements needs a sufficient amount of design flexibility and can lead to multiple iterations.	**Obstacle 3:** In the third level of the game, the team players were given the option to replace a building component with another recovered element calling for a change in the design.

Table 5: Reality worksheet: Game Scenarios

7.1.3 Play

This stage is focused on designing game-specific elements to ensure the 'playability' of the game. To achieve 'Playablity', it is the responsibility of the game designer to fulfil the criteria of engagement, fun and immersion. The following paragraphs describe in detail the game elements and their significance.

Game Objective: The main objective of the game is to 'Design a building with maximum usage of Recovered building elements' while making use of the existing online market places and available resources to facilitate the process. The 'Building layer' board is used as the scoreboard for the game. Depending upon the available resources, the players are asked to indicate which components on the layer board will be sourced as recovered building elements.

Main Game Board: The game board was developed as shown in the figure 15 using an available template. The four phases of the design process are highlighted using one colour each. At the end of each phase, a checkpoint is introduced where the players are required to check with the game master if the responses and decisions are consistent with the objectives of the game. One sprint of the board is one round of the board from square 1 to 45. Three obstacles and four tasks are placed along the route corresponding to the phase.

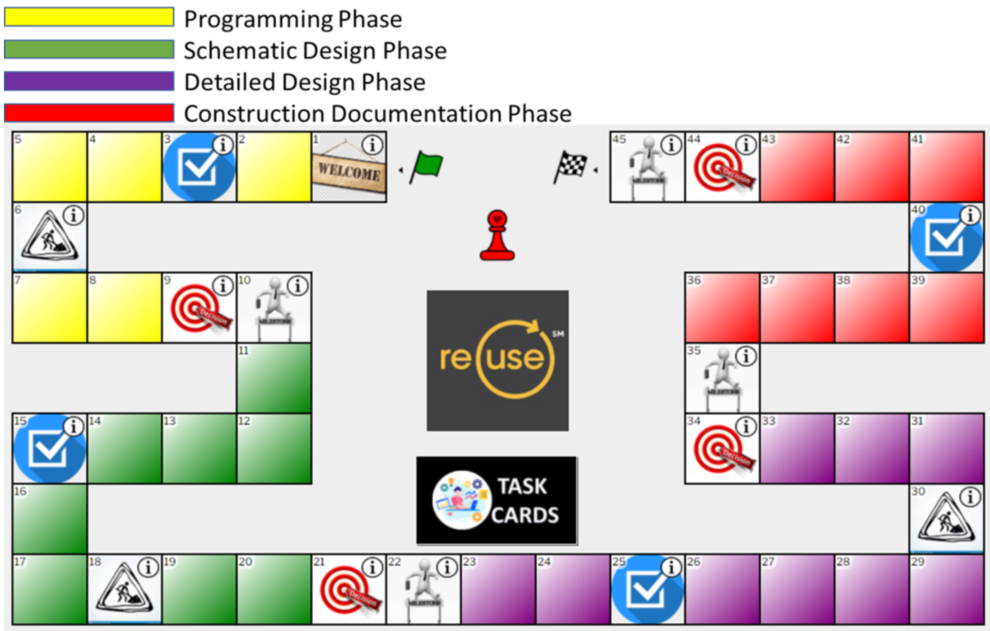

Figure 15: Game Board

Building Layer Board: The 'Building Layer Board' as shown in figure 16 is used to represent the Building Shearing layers (refer figure 43). The board is divided into six shear layers column-wise. Under each shear layer, the corresponding components are placed. This is not an exhaustive list of all the components of a building. However, it serves the purpose of the game. The board is provided with three tags as shown at the bottom of the figure 16. At the end of every stage, the team players are asked to fill the layer board to indicate their decisions. The team players can drag and drop the tags on any block of the layer board. The green coloured 'old' tag is used to indicate the components if they are sourced from an existing building. The yellow coloured 'new' tag is used to indicate the components that will be newly sourced and are made out of raw materials. The red coloured 'final' tag is used for both old and new components to declare that the decision is final.

Roles: Considering that the focus of the game was on understanding the dynamics during the design phase of a building project, the team players represented the main actors of a 'Building Design Management System'. The game requires the involvement of at least 4 players to act as 'Client', 'Architect', 'Structural Engineer' and 'Life-cycle Analyst'. It is to be acknowledged that in practice the number of members in any design team and the team composition can vary. Important criteria while selecting the team players is that they should have sufficient expertise based on their respective roles. As the main objective of this game is to collect data based on the interactions amongst the team players, adequate knowledge in the field of building design is essential.

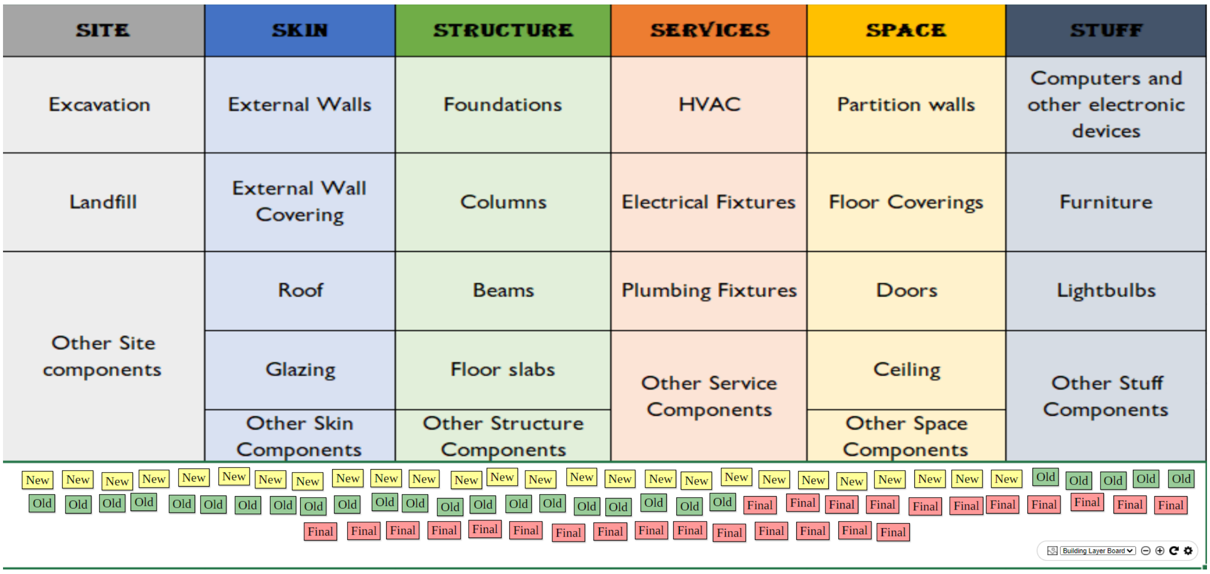

Figure 16: Building Layer Board

Task Cards: The task cards contain details of the four tasks that are integrated into the game. The details of the tasks and their connection to reality are mentioned in table 5. The exact wordings of the tasks as depicted in the game is shown in figure 39 of the Appendix. E.

Obstacle board: The obstacle board contains details of the three obstacles during the game. The details of the tasks and their connection to reality are mentioned in table 5. The exact wordings of the tasks as depicted in the game is shown in figure 40 of the Appendix E.

Client Requirements and Specifications: The players were provided with a short description of the client requirements and specifications at the beginning of the game. The main objective of the client is to set an example by developing a niche office building project with maximum integration of recovered elements. Full detail of the client specifications can be seen in figure 41 of Appendix E.

Existing Building stock: A fictional building project is introduced in the game with a brief overview of the building age, geographical location and structural configuration. Full detail of the building stock can be seen in figure 42 of the Appendix E.

7.1.4 Playing the Game:

The following section gives a step-by-step process of playing the game.

- The main game board is used as the primary board of instructions throughout the game. The game begins with the communication of the client requirements to the players.
- With this clarification, the players are asked to move forward by placing the pawn in the first square. From here on, the players are required to obey the instructions mentioned in each square.
- The blue squares with the 'check box' icon is used to indicate the tasks and the players are required to pick up the corresponding task card. The white boxes indicate obstacles and the players are required to go to the obstacle board and face the obstacles. For every task and obstacle, the players are encouraged to discuss and arrive at a decision together.
- When the pawn lands on the red square indicated with the 'target' icon, the players are required to go to the building layer board. Based on the provided conditions and client expectations, the players need to discuss and arrive at a final decision on the components. After placing the corresponding tags on the layer board, the game master who is also the client is asked for approval. This same pattern is followed at the end of each phase.
- In the end, the layer board is checked to see if a decision has been made for all the components and verified against the initial goals and objectives.

7.2 Data Gathering and Analysis

The gameplay session was focused on subjecting the players to a simulated environment of designing a building with the inclusion of recovered materials and components. The game was played by experts in the industry who were required to stay true to their roles and provide adequate justification to the decisions taken during the game. The session was roughly divided into three stages as mentioned below. Section 7.2.1 discusses in detail about the analysis of the data collected during the game.

- **Introduction to the game:** The session started with an instructional presentation of the objectives and rules of the game. The players were then provided with all the necessary resources such as the links to the board, task sheets and online resources. The players were asked to deliberate and enter their final responses in the task sheets. Once the game started, the researcher was only responsible for moderating the game with respect to the time and rules. All the decisions within the game were left to the discretion of the game master.

- **Game session:** Once all the instructions were made clear by the researcher, the game was initiated by the Game Master. The Game Master, who also assumed the role of a 'Client', was responsible for mediating the discussions amongst the players. The players had to ask the final decision of the Game Master to cross each level. Considering that the course of the game was highly dependent on the decisions of the team players and the Game Master, a measurable target or goal was not defined. In order to achieve the game objective, the players were expected to have made a decision on all the squares of the building layer board. The success of the game with respect to achieving the goal of collecting valuable responses to the scenarios relied completely on the productive discussions among the players.

- **Feedback:** The session concluded by asking a set of questions to the team players. These questions were focused on understanding the challenges faced by the players while arriving at a decision after each level and was included as the fourth task of the game. The players were encouraged to reflect on how the challenges were overcome during the game and if they could not, what can be the possible solutions. Finally, the players were asked for their feedback on the game in general.

7.2.1 Results from Game

As explained in the research methodology section of Chapter 4, the results from this data will be used to derive the key variables for the development of the Causal Loop Diagram. The game session was recorded and transcribed for analysis. In order to avoid redundancy, the transcripts are not attached to this report. The transcripts of the game were analyzed by using the method of coding qualitative data. Coding is the process of labelling and organizing the qualitative data to identify themes and relationships between them. Coding can be of two types, namely, inductive coding and deductive coding (Skjott Linneberg & Korsgaard, 2019). While inductive coding derives codes directly from the data collected, deductive coding uses a set of pre-defined codes to analyze the data. In this case, a combination of deductive coding and inductive coding was used. As mentioned before, key variables are basically the key words used to defined the causes and effects corresponding to project scenarios. Based on the literature study and expert interviews, pre-defined codes we used to define the causes of the game scenarios and thus constitutes the deductive coding of the data. The responses to the game scenarios were indicative of the effects produced as a result of the actions initiated by team players. Thus, the coding of these responses constituted the inductive coding of the data. Based on the identified codes, the key variables were finalized and the relationships between them were used to inter-link the variables while drawing the CLD. In total, 45 variables were derived based on the game responses which are listed in table 9 of Appendix F. Translation of game results to the key variables is an important step that decides the structural validity of the CLD. Considering the vastness of the data and the complexity of the model, the steps used to derive the key variables and causal loops are explained by focusing on one sample game scenario. Similar techniques are used for all the loops of the diagram.

The process of data analysis to arrive at the key variables for CLD is explained with the help of the figure 17. Based on the coding technique explained above, the process is undertaken using the following four steps: 1) Reality 2) Task 3) Response 4) Feedback. The keywords corresponding to each stage is captured and listed under it.

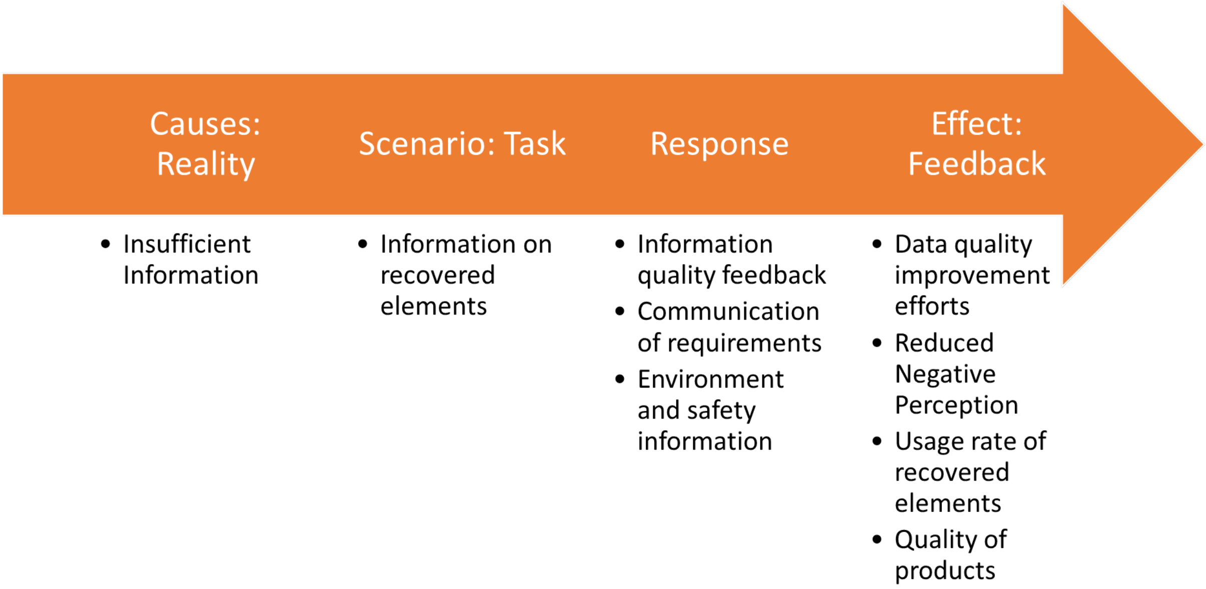

Figure 17: Derivation of Key Variables

Reality: From the literature study and the expert interviews, it was observed that the information provided by the online market places dealing with the supply of reusable elements is often **insufficient**. In order to decided the integration of a reusable element, the designers desire information on their quality, strength and environmental safety. Absence of such information results in propagating a negative perception towards the recovered elements.

Task: In order to demonstrate the scenario mentioned above, Task 2 was integrated in the game. As part of task 2, the team players were given the opportunity to explore the available online market places and communicate the missing/desired **information** pertaining to any product. This information was collected through 'Request Form' filled by the team players.

Response: The team players expressed that the market places mainly provided information about the product type and dimensions and in some cases, strength. However, they needed additional information with respect to the **environmental and safety** aspects of the product to be used. Filling the 'Request form' was an opportunity to clearly **communicate** what is desired by them. Facilitating such **feedback** systems to improve the quality of information can also help in eventually improving the quality of products.

Feedback: At the end of the game, team players were asked to reflect on the task and give their opinion on the perceived effects. The players were positive that a more clarity on the safety aspects and strength of the available products can give them more confidence to integrate reusable elements in their designs, eventually resulting in increased **usage rate.** Integrating the feedback mechanism will facilitate the easy communication of consumer needs and encourage the suppliers to focus on **product quality** improvement. One of the team players specifically mentioned that a 'reuse rating' may be incorporated as part of the feedback system similar to customer reviews available in popular online market places for consumer products.

7.3 Derivation of Sample loop

All the identified codes or key variables were connected logically using the above explanation, resulting in the development of a small part of the CLD diagram as shown in figure 18 below. Integration of a corrective action in the form of 'Information quality feedback' can facilitate the communication of requirements, eventually impacting the quality of information database and also the quality of products. Following the same procedure, each and every loop within the diagram was designed and leverage points were identified to propose corresponding intervention strategies. The next chapter discusses in detail the contents of the CLD diagram and their implications.

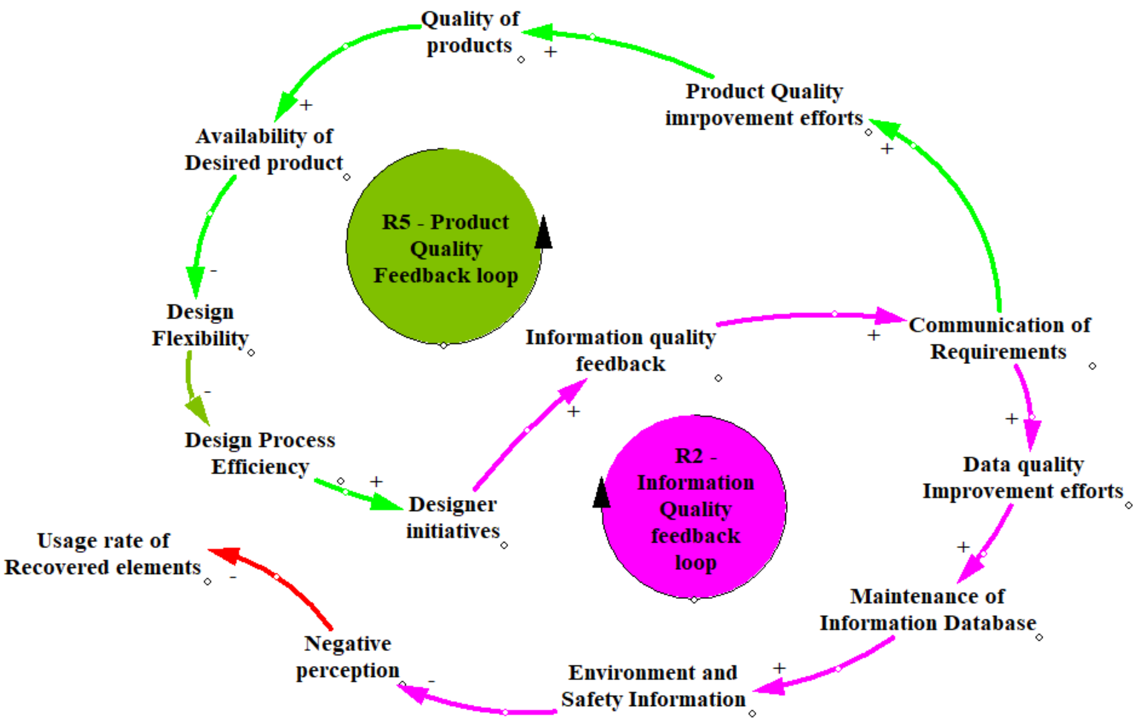

Figure 18: Loops R2 and R5: Sample diagram

Chapter 8

System Intervention Strategies

8 Results - System Intervention strategies

This chapter corresponds to the final phase of the systems thinking research framework - 'Causal Loop modelling'. Based on the variables derived from the game session, the CLD was modelled to generate patterns and feedback loops. The diagram was critically analysed to identify reinforcing feedback loops and balancing feedback loops. The intervention strategies corresponding to these feedback loops are established to be the fundamental guiding principles necessary for the development of a successful digital platform ecosystem. This chapter begins with giving a general overview of the entire CLD representing the Building Reuse System. This is followed by zooming into each of the feedback loops and explaining the minimum requirements criteria that each intervention strategy should fulfill.

8.1 Causal Loop Diagram

Based on the results from the game play session, it was found that there are 45 variables affecting the dynamics of a Building Reuse system. By connecting these variables based on their inter-relationships, the CLD was developed which contains a total of 10 feedback loops as seen in figure 20. Among these feedback loops, 6 loops are reinforcing loops which are indicated with brightly coloured circles and 'R' at the center. The relationship arrows are given similar colors to show the connected variables corresponding the loops. While the remaining 4 loops are balancing loops indicated with hexagons and 'B' at the center. The diagram revealed that the system is based on a series of reinforcing feedback loops that reinforce the power from the demand side of the market to the supply side and vice versa. Ideally, implementation of the intervention strategies corresponding to these reinforcing feedback loops should guarantee an exponential growth of the platform ecosystem. However, upon critically analyzing the diagram revealed that the platform cannot attain an ever increasing growth with the application of these strategies. The CLD contains 4 balancing loops which can lead to the collapse of the model and must be given special attention while designing the platform. The following section explains in detail the derivation of each loop and what it means to the system.

8.2 Reinforcing loops

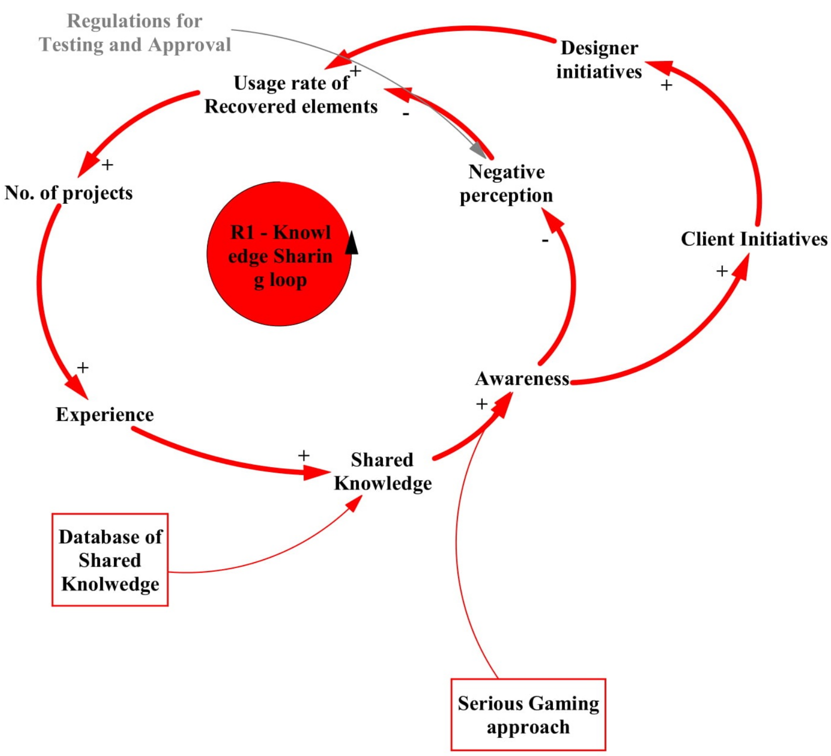

Figure 19: Knowledge Sharing loop: R1

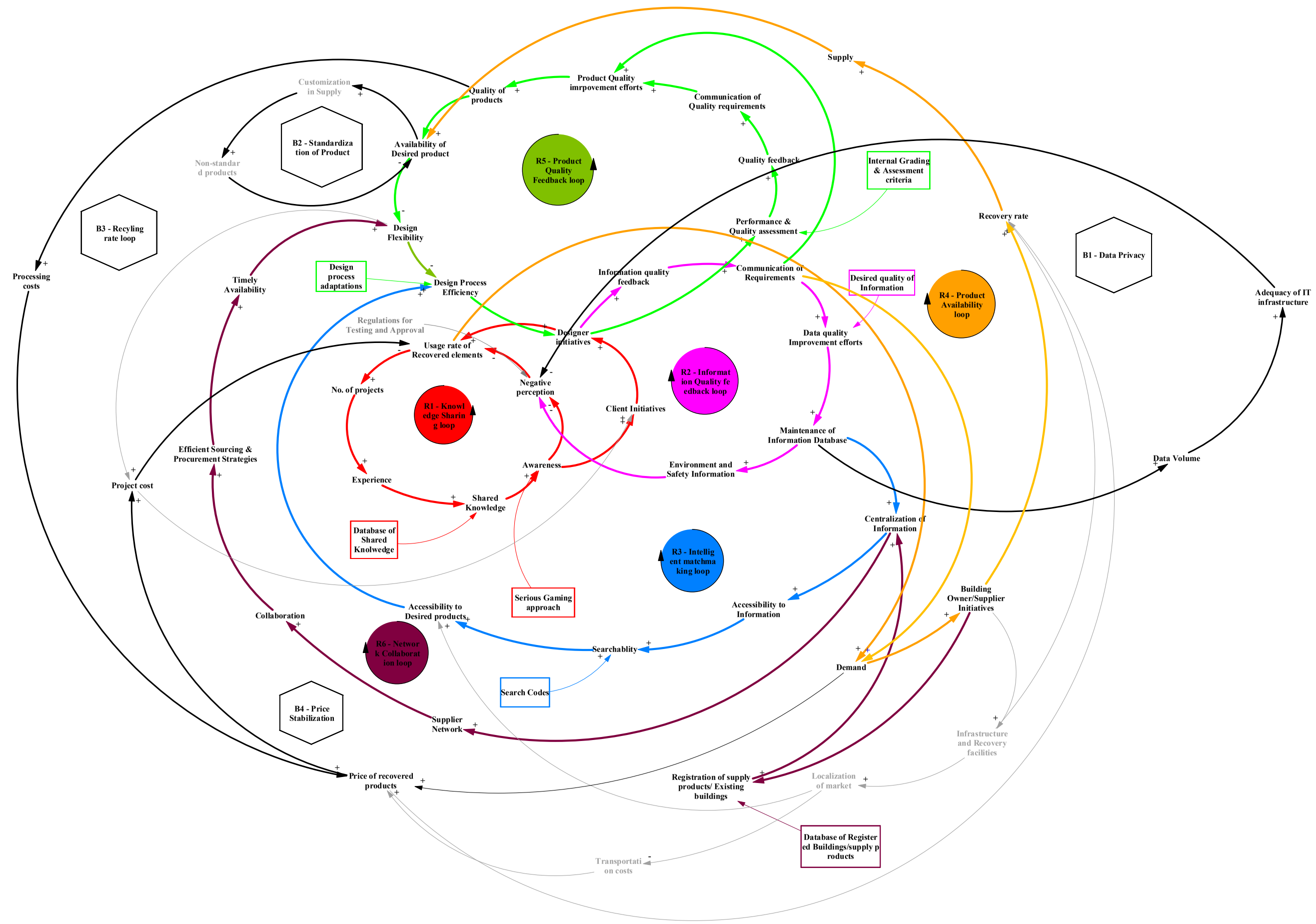

Figure 20: Building Reuse System CLD

1. Knowledge Sharing loop (R1): The knowledge sharing loop shown in figure 19 , contains variables that look at the social aspect of the system. For the reuse of building elements to become a conventional practice, it needs to be widely accepted by the society at large. To begin with, the acceptance can be initiated when designers and clients start taking initiatives to include such elements in their projects. Through the game play session, it was observed that the designers are motivated to experiment and innovate using such recovered elements. However, this could be made possible only when there was sufficient support from the clients. The clients are often unaware of the advantages of adopting reuse strategy and the lack of awareness leads to the negative perceptions affecting the usage rate. Besides, the loop suggests that the quality of shared knowledge can only be improved when clients or designers are willing take risks with such projects. The absence of 'Regulations for Testing and Approval' has emerged as an important cause for the negative perceptions amongst the clients and designers. However, this factor cannot be restricted to the limits of a digital platform ecosystem. Development of standards and guidelines for testing and approval falls within the jurisdiction of the government regulatory bodies.

Criteria: This issue can be tackled by maintaining a database of knowledge which is **accessible to all** the direct and indirect stakeholders of a project. This can include vast variety of knowledge modules ranging from recommendations for reuse of a particular component/material to best practices involved in deconstructing a building or designing a building with recovered elements. It needs to be emphasized that this **database generation** must not be restricted to the demolition contractors or designers, but to multiple stakeholders such as suppliers, waste processing companies, government regulators, etc. Besides, it is essential that a general awareness on the advantages of using recovered building elements must be promoted. While generating large amounts of database can become monotonous, other **innovative approaches** to educate the stakeholders may be adopted. For the purpose of this study, the simulated game environment was developed to provide a hands-on experience on such projects. However, such fun and interactive learning modules integrated with the digital platform can help in increasing awareness. Besides, initiating conversation through discussion forums can also be an interesting approach to encourage **community thinking**. As mentioned before, the variable of 'Regulations for Testing and Approval' cannot be integrated as part of the digital platform. However, these guidelines can be eventually stored in the knowledge database to ensure easy accessibility.

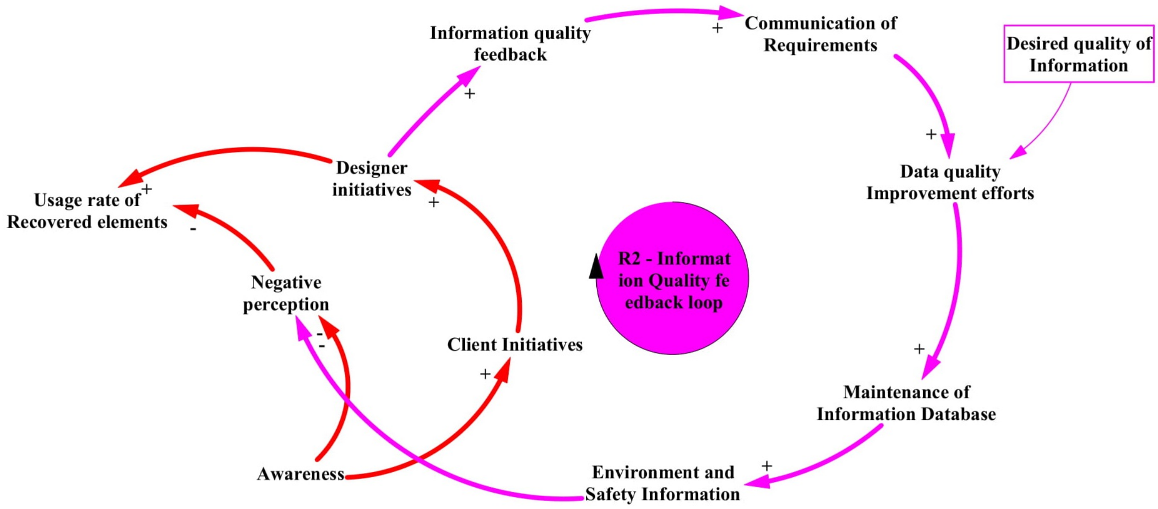

Figure 21: Information Quality loop: R2

2. Information Quality feedback loop (R2): The information quality feedback loop shown in figure 21 contains variables that focuses on the desired quality of information. It has been discussed previously that retrieving information from existing buildings is often difficult due to the lack of digitization and complex designs. Absence of sufficient information is one of the most important factor restricting the acceptance of recovered elements. When the players were asked to explore the online marketplaces for recovered elements, it was found that the information provided is not sufficient. In addition, the facility to interact with the suppliers was absent in some cases of if available, needed extra time and efforts. Currently, there is enormous pressure on the demolition contractors to develop inventory of components and materials before demolition. The information contained in the inventory documents are generally restricted to type of material, composition, function and dimensions. For the larger acceptability and reduced negative perceptions, there needs to be more clarity on the environment and safety factors. Providing regular and sufficient feedback on the quality of information can help in the clear communication of the needs and wants of the demand industry. This loop thus implies that it is not sufficient to develop a database structure, but there should be a facility to interact with the suppliers to ensure the continuous development in the quality of the data available.

Criteria: For any platform ecosystem, the data stored within it constitutes the foundation of the platform infrastructure. The development of material passports can seem to be the most probable intervention strategy for generating the database of necessary building information. However, the current supply industry is often not able to cope with the standard and intensity at which the information is desired in material passports. An important reason for this gap is that currently, the material passports are mainly developed for the new building projects with the hope that this information will be useful in the future. While there is no doubt that material passports can prove to be an excellent solution to store building information data in the future, their reliability for existing buildings where information retrieval is difficult, is still a concern. For a digital platform ecosystem catering to the reuse of existing buildings, a **modified database structure** that is similar to the building inventory documents may be introduced. This can also bring in a common consensus amongst the suppliers about the reuse-specific information desired by the demand industry. A standard database structure with **monitored information quality** at the input stage plays a significant role. During the game session, the players expressed particular interest in improving the quality of information through regular feedback or by sending queries. The success of most digital platform ecosystem is based on their constant efforts to improve based on **customer feedback**. Similarly, introducing simple feedback forms or queries can help in effective communication of the requirements of the users. This need not be restricted to the quality of information but also extended to the general functionalities of the digital platform ecosystem.

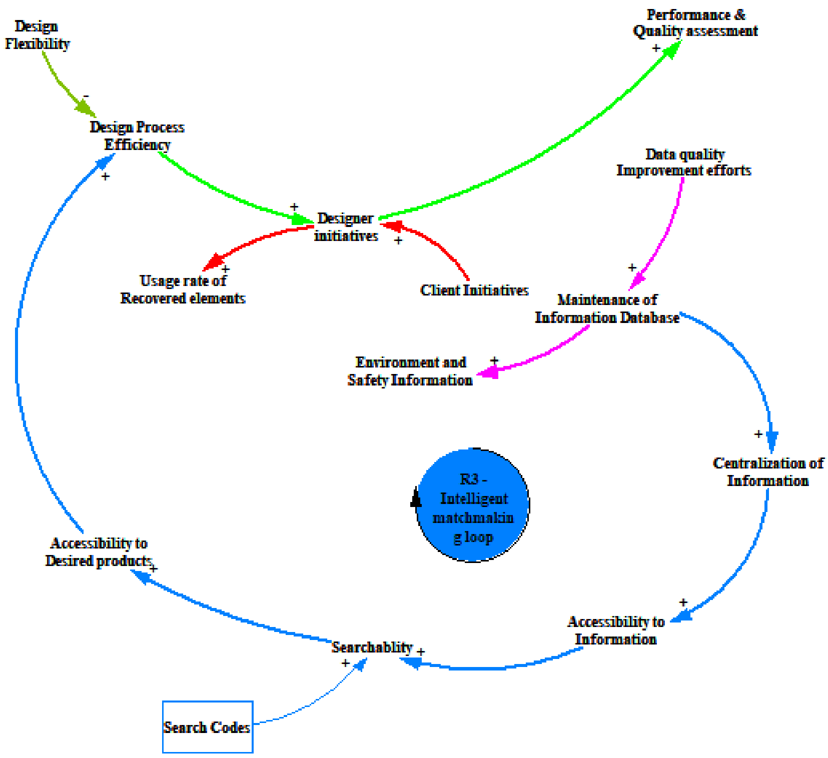

Figure 22: Intelligent matchmaking loop: R3

3. Intelligent matchmaking loop (R3): The intelligent matchmaking loop shown in figure 22, contains variables that focus on improving the accessibility to information and products within the system. While there is sufficient focus on improving the deconstruction processes, both in theory and practice, there is relatively less information on the adaptations needed during the design process. It needs to be acknowledged that the designing by integrating recovered elements will require major efforts and it needs to be channeled in improving the design process efficiency. The supply industry is fragmented at many levels currently as demolition companies and suppliers choose to establish their own online marketing platforms. Consequently, the availability of the right type of product at the right time is not being ensure, affecting the design process. During the game play session, the players were encouraged to search for recovered elements online. It was inferred that the available information is often incomplete or insufficient and is spread across multiple websites restricting the accessibility and consequently creating an impression that the supply is limited. While there is sufficient focus on what an information database should contain, this information can be practically of no use if it does not reach the relevant stakeholders. Restricting the platform to centralization of information and maintenance of database is not sufficient. There needs to be special emphasis on improving the "searchability" of the desired information by taking advantage of the IT infrastructure.

Criteria: The digital platform ecosystem has a huge role to play in improving the accessibility of information and consequently the accessibility to desired products. The inherent gap between the supply industry and the demand industry is often due to the missing link that brings them together. Developing **intelligent matchmaking tools** by taking advantage of Artificial Intelligence technologies is not a new concept and has already been tried and tested in many industries. As discussed in section 2.2 of Chapter 2, Exchange Material Platform has embraced the idea of intelligent matchmaking. However, the platform is currently available exclusively for the users and the matchmaking is highly-product specific. Matching at a product level and hence, sourcing from multiple suppliers for a single project may be feasible for the industries where products and processes are more or less standardized. For a highly complex construction industry, this option is not always feasible, especially in a situation where supply chains are not established for reuse. During the game session, the players were given the option to choose between working closely with a demolition contractor or multiple suppliers from the market. The option to work with the demolition contractor was more attractive as majority of the supply needs could be sourced from one location. Thus, the intelligent matchmaking for a building reuse ecosystem should rise above product specific matching to a **project-to-project level**. Considering that the timeline of deconstructing a building and development of a new building project is largely different, there is always an uncertainty regarding the timely availability of desired supply. Matchmaking tools should thus, also facilitate **matching based on timelines**. Above all, the platform should be **openly accessible** for all the users to at least view the available information. While considering the financial aspect of a platform ecosystem, it may seem viable to make the platform accessible to the paid members. However, it is highly difficult to attract users to join the platform ecosystem without showcasing the perceived benefits. This aspect will be elaborated more in the 'Network Collaboration' loop.

4. Product Availability loop (R4): The product availability loop shown in figure 23, contains variable that focus on the availability of desired product to the demand side of the system. This loop can initially be perceived as an obvious loop as it entails that the availability of desired product relies on an increase in the supply rate. The increase in supply rate is naturally the result of an increase in demand. However, the Building Reuse system is at a state of infancy. Relying solely on increase in demand is not practical as the suppliers are not able to meet the desired quality and quantity of products. Naturally, increase in demand, although an obvious cause to increase the supply rate, is not feasible in the short run. In order for the demand to increase, the designers should be convinced that the supply industry has the potential to provide the desired products. On the other hand for the supply industry to adapt their processes and strategies as per the demand needs, they must be well informed about their requirements and specifications. This is why the 'demand' variable is traced back to the variable 'communication of requirements'. Creating a 'feel' of the demand by openly communicating the requirements and design specifications will encourage the supply industry to adapt accordingly. This will naturally have an impact on not just the quantity of the recovered building elements, but also on the quality. Availability of right type of product at the right time will improve the design process efficiency at large and increase the demand in the long run.

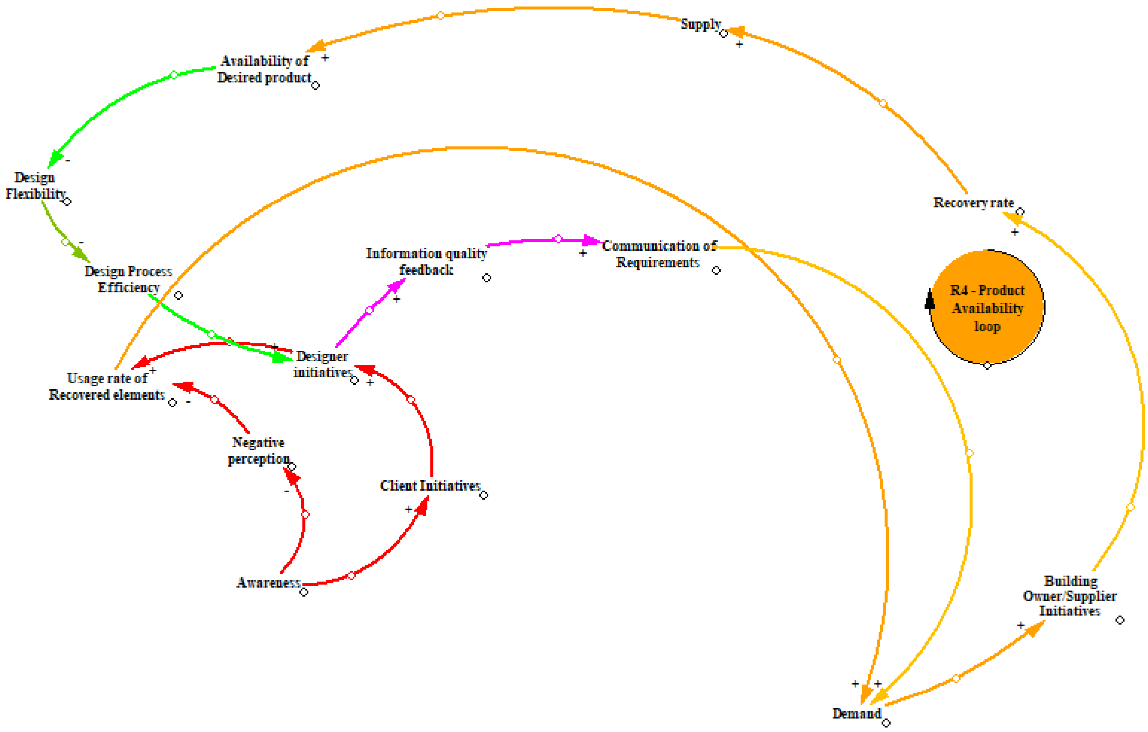

Figure 23: Product Availability loop: R4

Criteria: The intervention strategy corresponding to this loop can be as simple as **mitigating the communication gap** between the two sides of the system. The digital world offers multiple options when it comes to communication between two parties. It can be argued that the **commercialization** of construction industry to such a level where communication of requirements can happen easily over a chat or advertisement is not possible. This is exactly why most of the efforts in the industry are currently focused on capturing maximum possible information of a building which in turn gets stored in online data repositories. This can make the process of communication more transparent in the sense that the designers/architects will be able to review all the information in advance. However, this very process is slowing down the industry and adding to the complexity layers. The digital platform ecosystem should facilitate the communication of requirements starting from a very basic level. Facebook market place can be seen as a good example in this direction. The sellers and the buyers are able to post their requirements in the form of advertisements containing a few words. The building industry is not completely oblivious to this practice of posting advertisement. Inviting bids for the process of tendering usually starts with an **advertisement**. This type of basic communication can help in initiating the first point of contact between the supplier and the customer and accelerate the establishment of Building Reuse system. The need to generate massive database of building information upfront can be eliminated to some extent which can consequently improve data privacy. By taking into consideration that the supply chain for reuse is still at an initial stage of development, relying on it to ensure the availability of product is not sufficient. As a kick-starter, the two sides of the industry should collaborate at a project-to-project level. This can ensure effective **collaboration** and eventually lead to the establishment of supply chain network.

5. Product Quality feedback loop (R5): The Product Quality feedback loop as shown in figure24 contains variables that focus on improving the quality of the recovered building elements. Assigning the responsibility of improving the product quality to designers may seem unconventional at first. However, upon comparing the logic to other industries, it can be seen that the improvement of product quality directly depends on the customer feedback. In this case, the designers are the customers and the demolition contractors are the suppliers. The quality of recovered elements will largely improve only when there is sufficient practice of feedback initiated by the designers. As the concept of reuse is still in an experimental phase, no prescribed quality standards are available currently. The obvious way of approaching this issue is to develop standardized regulations for testing and approval. In this case, the responsibility will be transferred to the governmental and regulatory authorities. In the long run, standard regulations are absolutely the best way of approach the problem. By taking into consideration the principles of commercialization in digital platform ecosystems, this loop links the responsibility of product quality to the designers. To facilitate such an initiative, the designers working on individual projects can develop internal grading and assessment criteria. Based on this assessment, feedback can be given to the suppliers which will encourage them to improve the quality of recovered elements. This can help in accelerating the efforts to improve the quality and also the quantity of the desired product at the right time, consequently improving the design process efficiency.

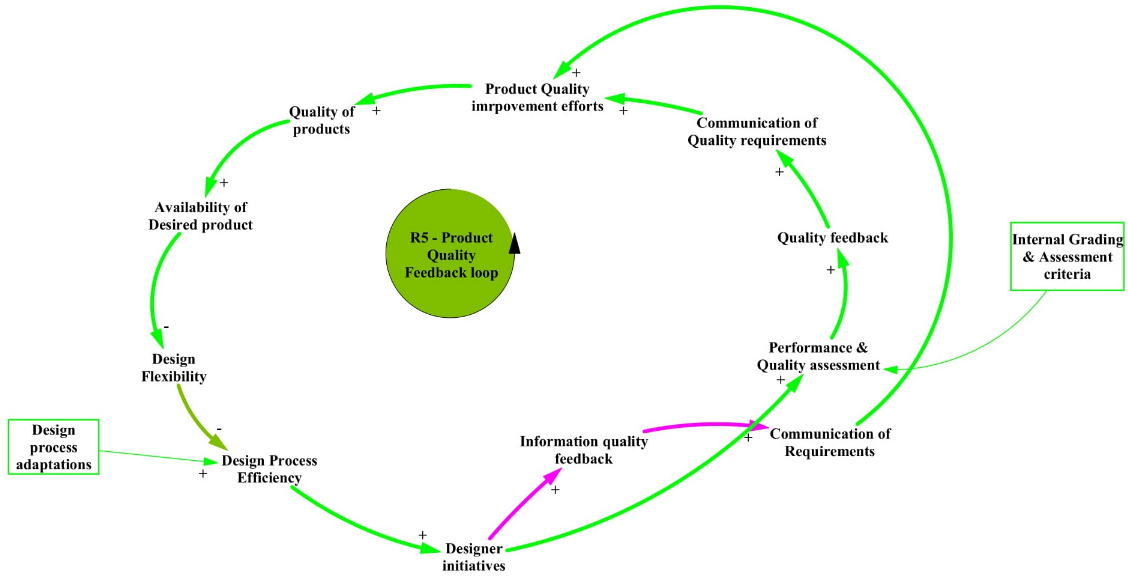

Figure 24: Product Quality loop: R5

Criteria: The intervention strategies adopted for this loop can be very similar to the intervention strategies of 'Information feedback loop' as both the loops largely depend on the **feedback system**. With the use of digital technologies, communication of the feedback can be facilitated through multiple options such as feedback forms, survey or through direct collaboration with the supplier. The extra added effort for this loop would be the development of **internal grading and assessment criteria**. In the game play session, a task related to the inspection of recovered elements was introduced before their approval. The team players came up with a checklist and suggested the necessity to link it to the **life cycle assessment** of the recovered components. The construction industry has slowly begin to adopt the practice of life cycle assessment of buildings by embracing the available digital tools. The feedback based on life cycle analysis can immensely support the demolition industry to invest their efforts in the right direction. Usually, it is expected of the supplier to give complete information of the life cycle of a product to the designers. Based on this intervention strategy, the suppliers are still required to provide maximum possible information to the designers. However, the responsibility of analyzing the durability and quality can be partially shifted to the designers. It needs to be emphasized that the researcher is not trying to declare that this is only possible solution. But it could be one of the possible solutions for effecting a change at an accelerated rate.

6. Network Collaboration loop (R6): The Network collaboration loop as shown in figure 25 contains all the variables responsible for the establishment of a network within the system. Actors constitute the foundational element of any system and are responsible for facilitating the processes and informational exchange and have the ability to steer the dynamics of any system. All the intervention strategies mentioned until now largely depend on the initiatives and responsibilities assumed by actors in the network. The term 'actors' implies that the stakeholders associated with the system need to 'act' for effective collaboration and establishment of network. In Building Reuse system, the actors can be broadly classified into two categories, one belonging to the supply side and the other to the demand side as explained in Chapter 3. Majority of the barriers in enhancing reuse will be solved by ensuring effective communication and collaboration amongst the actors. In the loop, the number of differently coloured arrows are indicative of the fact that the 'network' collaboration loop is at the core of the CLD. One of the primary functions of digital platform ecosystems is to facilitate the establishment of networks. If the building owners/ suppliers take initiative to make their presence felt in the digital space, it can lead to the centralization of information by channelizing it effectively. This will facilitate the accessibility of the designers/clients towards the supply industry.

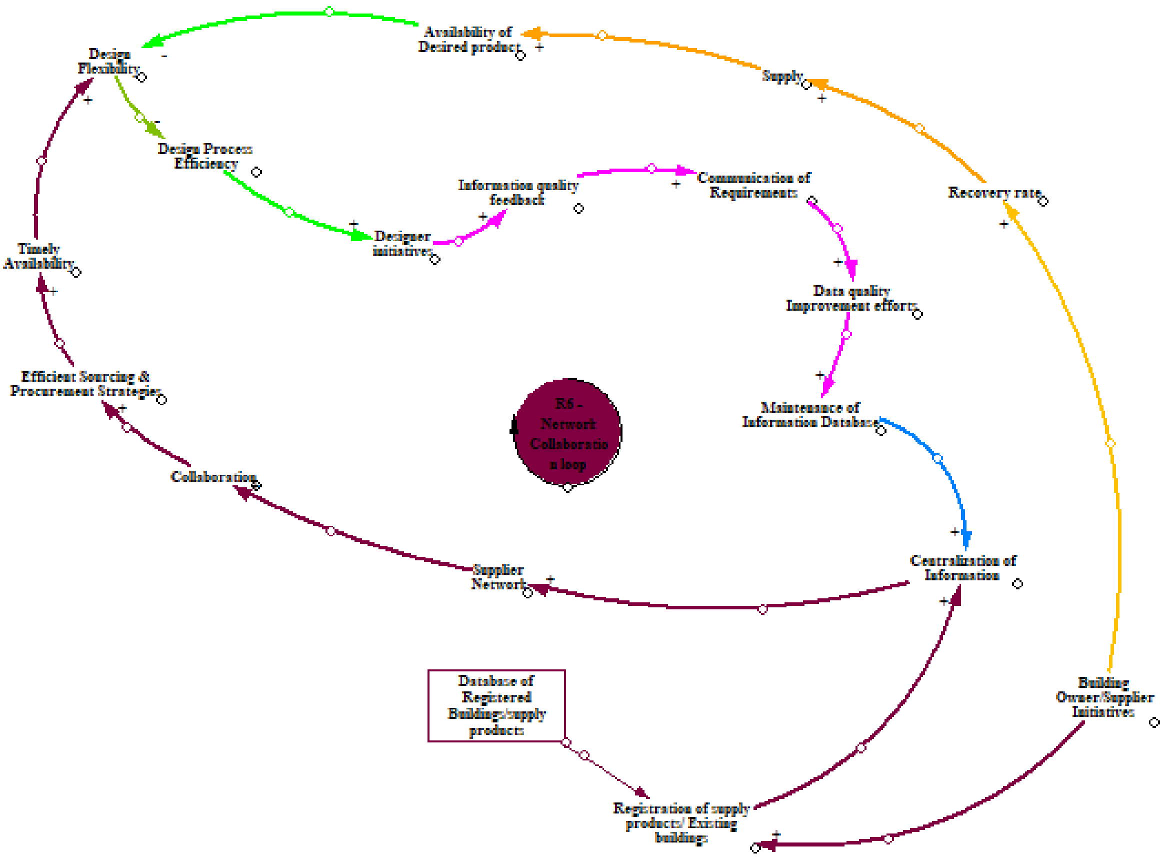

Figure 25: Network Collaboration loop loop: R6

Criteria: The fundamental factor that defines the success of any digital platform ecosystem is its ability to establish a **well-connected network**. With the evolution of digital space, the majority of the transactions in any business happens over the internet. As has been discussed before, the problem revolving around 'Building Reuse System' is not solely a technical problem. The formation of a well-functioning supply chain network is essential and digital platforms must be exploited to establish connections and facilitate **communication.** Usually, actors are the initiators of networking in the real world. For them to join a digital platform ecosystem, they must be convinced of assured benefits out of it. Stakeholders must be awarded **incentives** in the form of money, information, values, business, etc which in turn will strengthen the platform ecosystem. The business model of Airbnb can be seen as a suitable example in this regard. In this case, the 'suppliers' are the owners who register their rooms/houses with Airbnb. While the owners are incentivized through monetary payment for their rooms, the customers who use them are incentivized through the services offered by the room. Either party is benefited leading to the growth of the platform. Similarly, while developing a digital platform ecosystem for 'Reuse', the suppliers/Demolition contractors need the assurance that they will be able to find buyers through it. On the other hand, the customers of the demand industry must receive satisfactory options of recovered elements. Besides, the infrastructure of the ecosystem must provide a safe environment for the users. This is where the principles of data privacy and security come into the picture. Above all, the platform ecosystem must be **continuously emerging** based on the changing dynamics of the system. With increased expectations comes increased responsibilities to improve the services.

8.3 Balancing loops

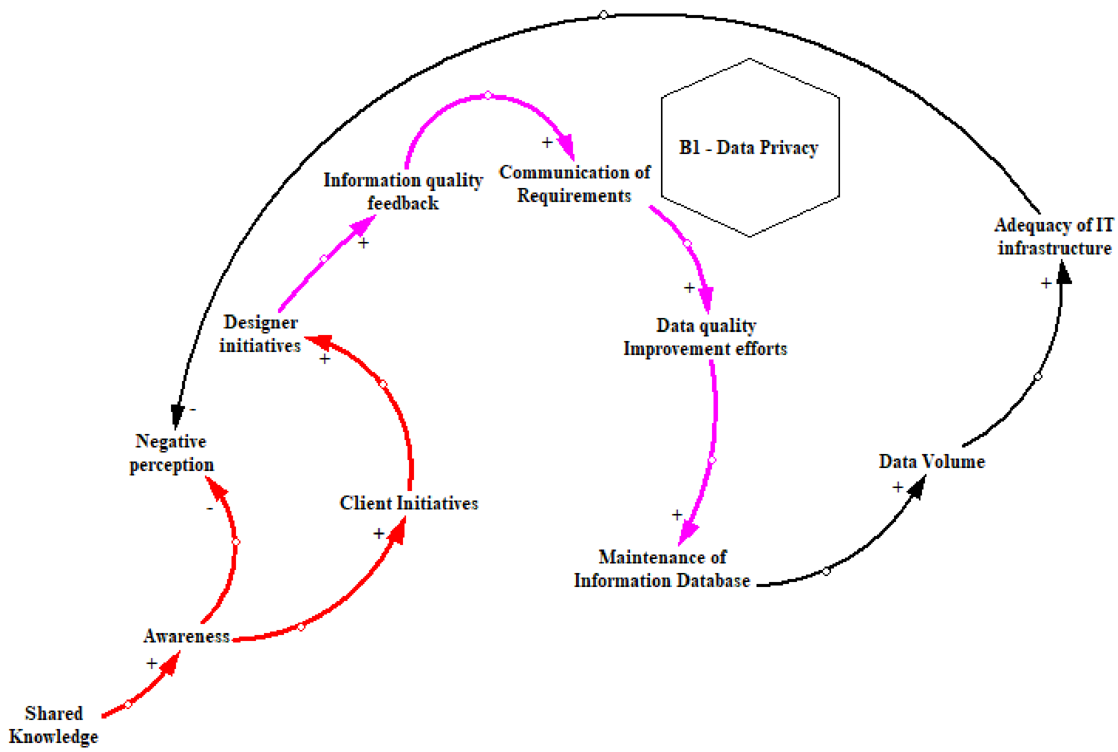

Figure 26: Data Privacy loop: B1

1. Data Privacy (B1): The necessity of information centralization and maintenance of the database has been stressed significantly in the previous sections. With the increased inflow of data volume, there is an inherent risk of breaching the data privacy and security of the users. The IT infrastructure needs to be adequate to provide a safe digital space to all the users. A modern digital solution such as 'Block-chain technology' can be useful to balance this loop. If the digital platform is not safe, it will increase the negative perceptions amongst the stakeholders and an attempt to increase the collaboration over digital space will be curbed.

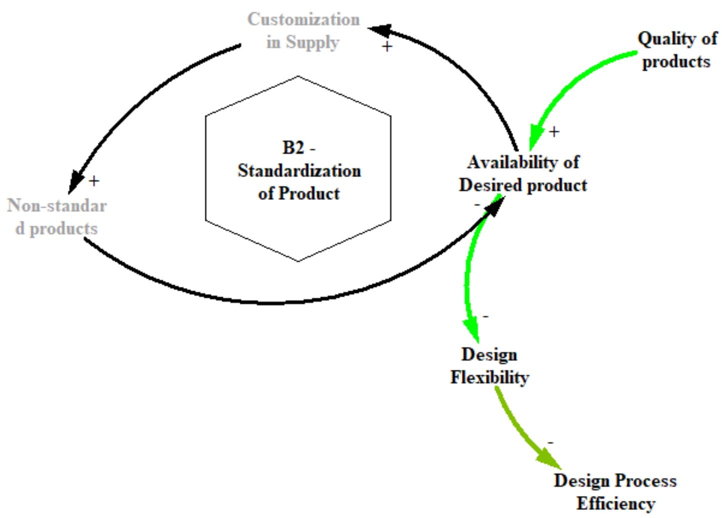

Figure 27: Standardization of Product loop: B2

2. Standardization of Product (B2): The designers/architects are often discouraged to integrate recovered elements in their design because of the limited variety of options. Working with the available options adds to the complexities in design and leads to multiple iterations. By the implementation of the intervention strategies mentioned above, there can be an increase in the customization of the available option. The supply side of the industry may go the extra mile to provide suitable options based on the type of project and requirements. In the long run, this can lead to the production of non-standardized products. If we take the case of the automotive industry or any other large scale manufacturing industry, the production is undertaken at a large scale because of the standardization of the product. Similarly, to maintain a building element in the reuse loop, the industry must attain some level of standardization for easy adaptability.

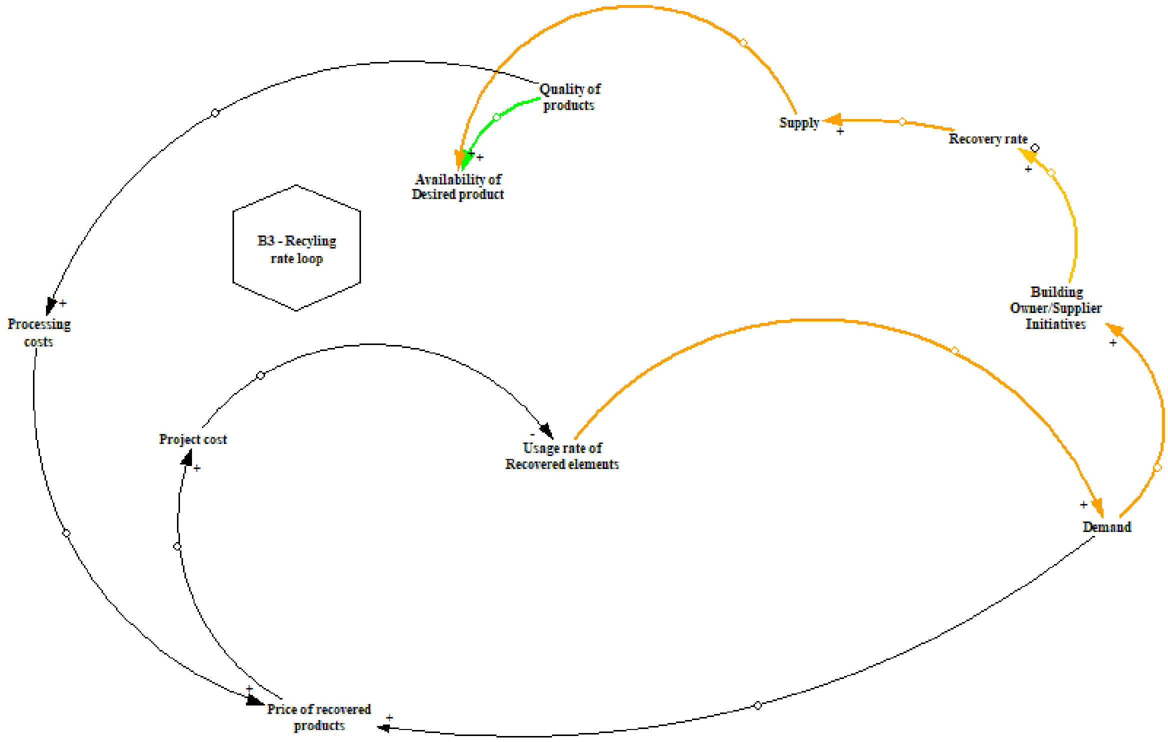

Figure 28: Recycling Rate loop: B3

3. Recycling Rate loop (B3): This is one of the most prominent reasons that can hinder the reuse rate of building elements. All the intervention strategies stress the need to develop the quality and the availability of the recovered elements as per the needs of the demand industry. While it is highly essential to meet these criteria, there is a high risk of falling back to where it all started. In the problem context analysis, it was seen that the economic advantage and technical feasibility that recycling offers over reuse is affecting the recovery rate of reusable elements. If the supply industry is subjected to the added pressure of providing excellent quality products, it will have an impact on the recovery and manufacturing process. Consequently, the processing costs will increase which would further discourage the demand industry to purchase recovered elements. A decrease in demand will further, affect the initiatives taken by demolition contractors/suppliers and eventually affect the recovery rate. This situation can be mitigated only with the increased efficiency of the infrastructure and processes involved in deconstruction and recovery. Besides, governmental regulations of integrating recovered elements must be introduced as a mandate to maintain high demand.

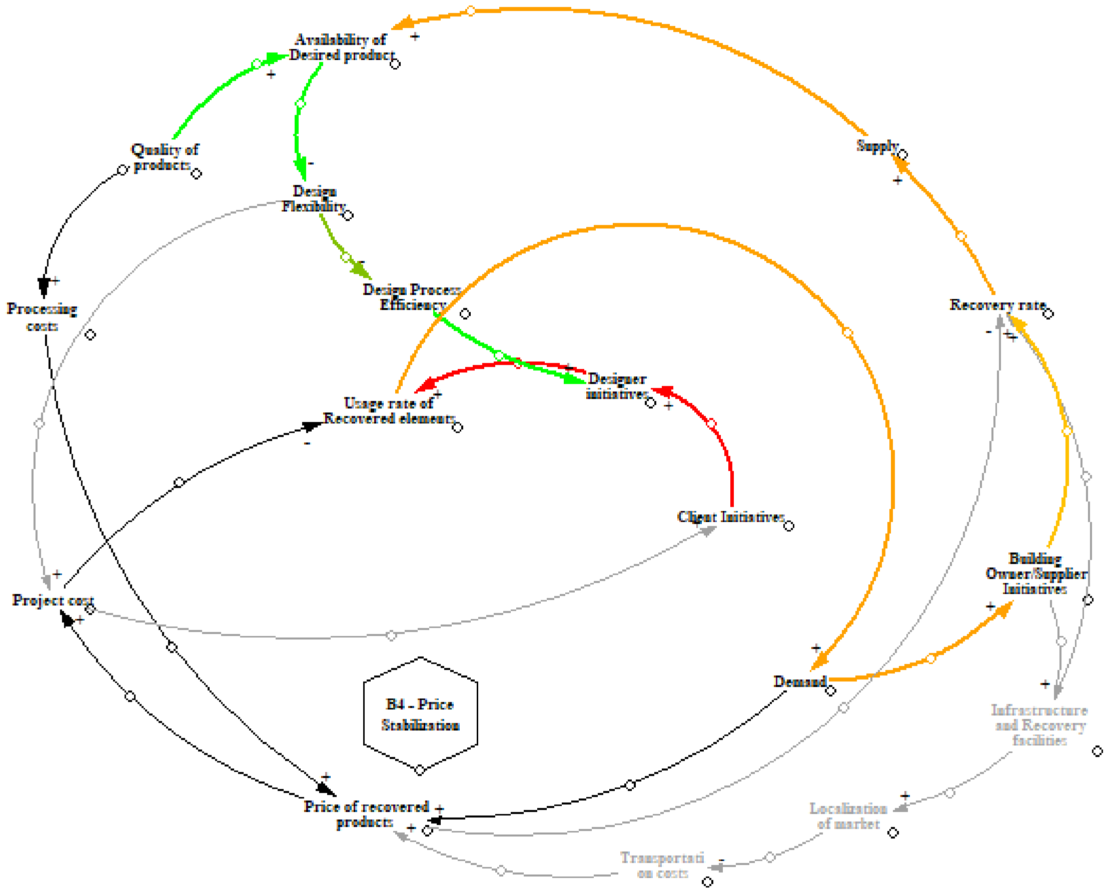

Figure 29: Price Stabilization loop: B4

4. Price Stabilization (B4): Price stabilization is the most obvious balancing loop that needs to be addressed in any CLD that focuses on the issue of supply-demand mismatch. Through the reinforcing loops, it can be seen that all the power is channelled towards improving the quality and quantity of recovered elements. The increased efforts to satisfy the needs of the customers can eventually lead to an increase in the overall cost of the product. If these options are not economically feasible, it will have an impact on the rate of demand, again leading to the mismatch in supply and demand. This is similar to the popular 'chicken and egg' problem. By exploiting the strength of digital tools, the digital platform ecosystems should be able to channelize investments and expenses in such a way that price is stabilized.

8.4 Conclusion:

This chapter discussed the development of CLD based on the results from the serious gaming. Multiple leverage points were identified through the critical analysis of the model. It can be concluded that the digital platform ecosystem for enhancing reuse will fundamentally rely on the intervention strategies corresponding to the reinforcing loops. The criteria that each reinforcing loop needs to fulfil is summarized in figure 30 given below. It thrives on the idea of reinforcing power from one side of the market to the other. The balancing loop can be seen as an alarm or red alert and needs to be given special attention to avoid failures. While these intervention strategies are relevant within the context of systems thinking, it is essential to translate these to make sense in the context of digital platform ecosystem. Chapter 10 gives an overview about the implications of these strategies on the platform ecosystem.

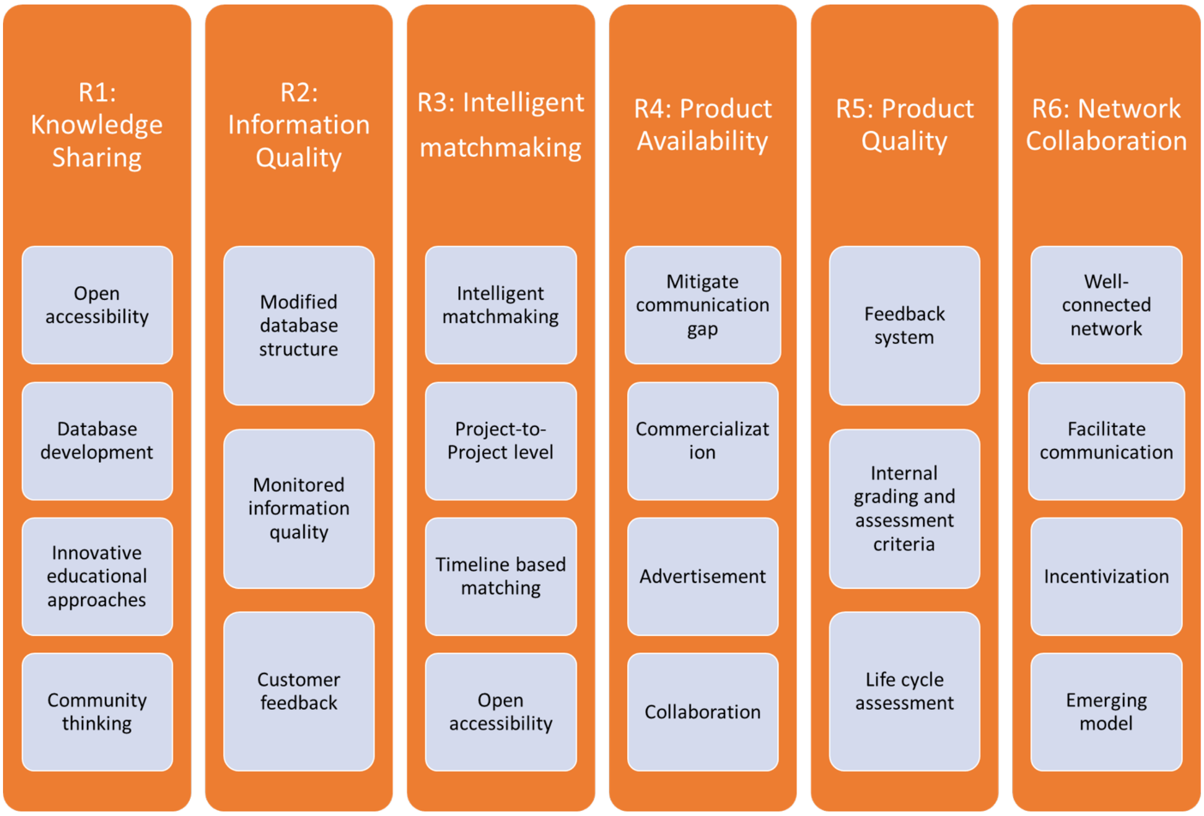

Figure 30: Intervention Strategies

Chapter 9

Validation

9 Validation

The validity of results derived from a model based on the systems thinking directly depends on the validity of the model structure (Barlas, 1996). Consequently, the validity of the intervention strategies as a holistic solution to the problem at hand, highly depends on the validity of the causal loop model. The most widely shared view of validation in the context of System Dynamic models is that it is a judgement of both usefulness and fitness of purpose (Mclucas et al., 2012). Thus, the validity cannot be absolute nor completely objective (Barlas, 1996). Based on the type of model and its purposes, multiple model validation methods can be found in the literature (Barlas (1996), Forrester & Senge (1980), Zagonel (2006)). As mentioned in Chapter 2, the main objective of this research is to investigate the application of 'systems thinking' as a holistic approach to enhance the reuse of recovered building elements. Thus, in this case, the CLD can be considered fit for the purpose if it can fulfil the objective of providing a holistic view on the problem. To establish the usefulness of the model, the intervention strategies are traced back to the barriers identified in Chapter 5. The added value of the systems thinking approach in addressing these barriers is investigated and the validity of the model is analyzed. This type of approach is similar to the 'Theoretical - Direct Structure test' of model validation. Theoretical structure tests involve comparing the model structure with generalized knowledge about the system that exists in the literature (Barlas, 1996). While other types of validation methods exist such as formal interviews, quantitative analysis of the variables, etc., the theoretical method is adopted for this study considering the limitations of time and resources. The following section explains the process of investigating the validity of the model as a holistic approach to the problem of reuse.

9.1 Investigating the added value of Systems Thinking approach

Every loop of the CLD can be traced back to a particular scenario of the real system. An evidence of how the real scenarios were translated to key variables of the CLD was provided in figure 17. Based on the same ideology, each loop was checked against the list of barriers identified in Chapter 5 and the barriers addressed by each intervention strategy are summarized in the table shown below.

Intervention Strategies	Addressed Barriers
R1: Knowledge Sharing loop	Negative perception, Limited awareness , Lack of trust, Absence of initiatives by clients/designers, Insufficient information
R2: Information Quality loop	Insufficient information about the environmental impact, Insufficient information, High Design cost, Limited supply of desired options, Poor quality of recovered elements
R3: Intelligent Matchmaking loop	Mismatch in supply and demand, High Design cost, Fragmented supply chain, High Design cost, Uncertainty in the timely availability of supply
R4: Product Availability loop	Mismatch in supply and demand, Fragmented supply chain, High Design cost, Limited supply of desired options, Flexibility in designs, Uncertainty in the timely availability of supply
R5: Product Quality loop	High Design cost, Limited supply of desired options, Poor quality of recovered elements, Flexibility in designs, No standards for compliance with health and safety regulations, Insufficient information about the environmental impact
R6: Network Collaboration loop	Mismatch in supply and demand, Fragmented supply chain, Flexibility in designs, Uncertainty in the timely availability of supply, Absence of initiatives by clients/designers, Inexperience, Limited skills

Table 6: Intervention Strategies and corresponding barriers

As shown in figure 14, the barriers were categorized into six different types, namely: economic, technical, regulatory, environment & safety, organizational and social. Considering the complexity and inter-dependent nature of the problem, each intervention strategy can be seen to have addressed barriers across multiple categories. Since the structural validity of the CLD model depends on its ability to provide a holistic solution, it is essential to check the number of barriers that were addressed across each category. In order to better visualize the number of addressed barriers against the total number of barriers, a graphical representation of the same was developed. To begin with, the total number of identified barriers, based on figure 14, are counted and mentioned in the first row of table 7. The second row indicates the number of barriers of each type that were addressed by any of the intervention strategies. The percentage variation in the number of addressed barriers against the number of non-addressed barriers is plotted in the figure 31.

	Economic	Technical	Regulatory	Environment and Safety	Organizational	Social
Total number of identified barriers	7	7	4	3	7	5
No. of addressed barriers	3	5	1	1	2	4
Percentage of addressed barriers	0.43	0.71	0.25	0.33	0.3	0.8

Table 7: Ratio of Addressed barriers to Total barriers

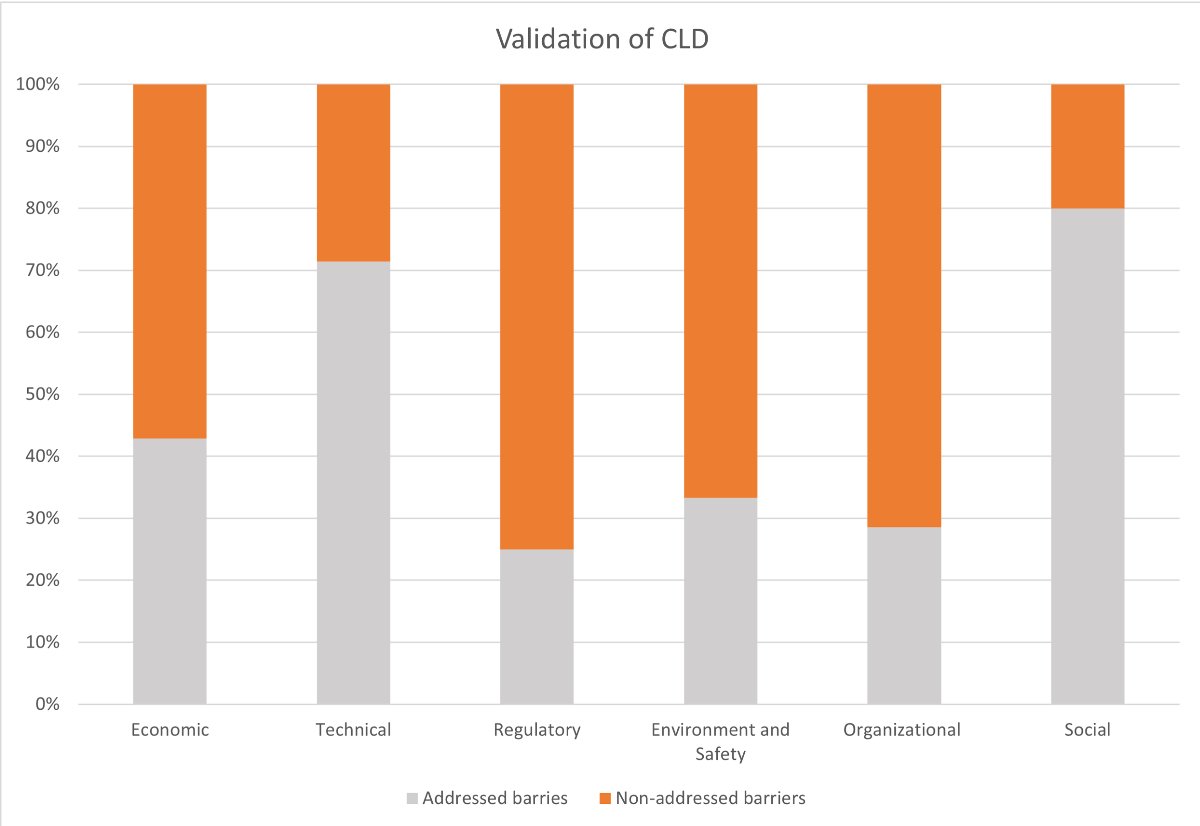

Figure 31: Validation of CLD

The following section discusses the observations derived from the graph. Through the lenses of a digital platform ecosystem, the researcher tries to analyze why certain barriers were addressed in the model and why certain others were left out. Finally, a conclusion is drawn regarding the structural validity of the CLD model and hence, the validity of the intervention strategies.

Economic: Out of the 7 economic barriers, the intervention strategies were able to address three barriers. The barriers concerning the enhancement of reuse in building components can be largely seen as an economical problem. The mismatch between the two sides of the industry or the two sub-systems concerning supply and demand can be attributed to the fragmentation of the supply chain. Several businesses with similar problems are thriving on the success of a good platform economy and hence, DPE seems to be a reliable solution. Besides, the barrier of 'high design cost' can be overcome through the stated interventions strategies. An increase in cost during the design processes are mainly associated with the uncertainty in the availability of desired recovered components at the right time. The designers are expected to be highly flexible with their designs and hence the high costs. Intervention strategies of 'product quality' and 'product availability' avoids the need to have a flexible design approach. The non-addressed barriers are mainly associated with the costs involved during the deconstruction and recovery processes as a result of the absence of sufficient technological solutions.

Technical: Majority of the barriers listed under the technical category are being addressed by the CLD model. Most of these barriers revolved around the non-availability of desired options at the right time.

Such uncertainties can have a significant impact on the design process and consequently add to the design costs. As mentioned in the economic category, ensuring the availability of products is predominantly a supply chain problem. The Revolution of the supply chain through platform economy will eventually reduce the impact of technical barriers. The only non-addressed barriers are concerning the technical complexities involved in the deconstruction process. It is important to note that the team players involved in the game were design experts. Consequently, the derivation of the CLD is majorly based on the technical perspective of the actors belonging to the sub-system - 'Building Design Management System'. This could be one of the reasons for a small bias towards consideration of the majority of the technical barriers.

Regulatory: Out of the 4 regulatory barriers, the model was able to address only one of the barriers - 'No standards for compliance with health and safety regulations'. Establishing governance mechanisms is an essential part of any digital platform ecosystem. While the development of standards and regulations lies within the jurisdiction of regulatory bodies, the deficiency can be overcome to a certain extent by taking advantage of the governance rules within the digital platform ecosystems. The idea of integrating an internal grading and assessment criteria for filtering out the products or suppliers who do not meet the expected standards can be used to overcome the said barrier. On the other hand, the remaining three barriers - 'Absence of regulatory framework for testing and approval', 'Absence of regulatory codes and standards for deconstruction', 'Absence of financial and regulatory incentives'; cannot be mitigated through platform ecosystems. It is expected of the governmental bodies to initiate actions in this direction.

Environmental and Safety: This type of barrier can be mainly attributed to the insufficient information about the environmental and safety aspects of the recovered elements. The necessity of having information about the toxicity of materials is equally important during the deconstruction as well as to take decisions during their integration in new designs. The intervention strategy of 'Information Quality' particularly addresses the necessity of having sufficient information based on the requirements. The two remaining two barriers that were not considered constitute 'Health and safety risks' during the process of deconstruction and 'absence of localization'. These two barriers are mainly associated with the lack of recovery and infrastructural facilities during the deconstruction process. Such barriers are expected to be overcome with the eventual advancement of the supply chain and development of needs and are beyond the scope of a DPE.

Organizational: The organizational barriers associated with limited knowledge and skills and hence, the lack of initiatives by the clients/designers are sufficiently addressed through the intervention strategies. The strategy of 'knowledge sharing' loop particularly focuses on these. Facilitating the sharing of information and knowledge by taking advantage of the network effects in a DPE is the desired approach. Besides, the barrier of inequality in the distribution of risk can be solved through contractual changes and cannot be accommodated as a problem within digital space. Finally, the easy accessibility to standard products stands as a major barrier. Clients or any concerned organisation always prefer to adopt the easy way and standard products with less risk will always be given priority; unless the government imposes strict regulations against them.

Social: Social barriers have been given the highest attention by the intervention strategies. The formation of a networked structure of actors is an important implication of having DPE as a solution. Collaboration amongst the actors through a networked structure is bound to develop community thinking eventually. Besides, the realization of the demand in the market will encourage the need to develop new business models. After a while, financial incentives will take precedence and social barriers will become secondary. The only barrier of 'occupational health concern' is left as it is associated with the safety aspects involved during the deconstruction process.

Conclusion: Based on the above discussions, the following conclusions can be drawn about the structural validity of the CLD model and hence the intervention strategies:

- Economical, social and technical barriers have received the most attention. The technical bias is mainly due to the involvement of design experts of the industry as the major source of input for CLD. The bias towards economical and social barriers is because of the type of solution proposed. DPE is fundamentally a solution towards developing a new economic model which relies on the networked collaboration amongst the actors.

- Development of a CLD by seeking inputs from several other actors of the industry can reveal multiple other leverage points. Thus, these intervention strategies are not exhaustive and must be regarded as appropriate for the specified context.
- Nevertheless, the model was able to touch upon all types of barriers and hence, can be accepted to give a holistic approach to the problem.
- The intervention strategies could easily be traced back to the causes of barriers under discussion. This is the evidence that the model was able to sufficiently represent the reality of the 'Building Reuse System under discussion.

Chapter 10

Digital Platform Ecosystems

10 Digital Platform Ecosystem

Until the previous chapter, the major focus of the research was on investigating the application of ST as a holistic approach. This resulted in the derivation of multiple intervention strategies establishing that the system thrives on a reinforcing growth model. In order to sufficiently answer the main research question, it is essential to understand the implications of these strategies on a digital platform ecosystem. This chapter begins by giving a detailed overview of the structure of any digital platform ecosystem as per the literature. This is followed by explaining the relevance of the intervention strategies while designing the structure of a digital platform ecosystem for enhancing the reuse of building components.

10.1 Building blocks of Digital Platform Ecosystem

The structural components of any Digital Platform Ecosystems can be broadly classified as: Activities, Actors and Architecture (Adner (2017), Hein et al. (2019), Kapoor (2018)). Activities in a DPE include the development of any type of application or provision of any services. These constitute the actions that determine the creation of values within the ecosystem. Actors consist of agents within the ecosystem who are responsible for initiating these activities. These actors take the role of complementors and are responsible for providing the desired services or products. Finally, the architecture defines the technological interaction that orchestrates the exchange between the supply and the demand sides of an ecosystem (Hein et al., 2019). For a platform-based ecosystem, the platform owner has the right to define the principles and rules of governance and hence, is responsible for defining the technological interactions. Based on this understanding, the digital platform ecosystem is defined by Hein et al. (2019) as *"digital platform ecosystem comprises a platform owner that implements governance mechanisms to facilitate value creating mechanisms on a digital platform between the platform owner and an ecosystem of autonomous complementors and consumers"* as shown in figure 32. Thus, 'Platform Ownership', 'Value Creating Mechanisms' and 'Complementor Autonomy' are considered as the three building blocks of a DPE. To given an example for better understanding; the popular platform Uber is a platform ecosystem in which the company Uber has platform ownership. It creates value through the activity of offering rides and the drivers are considered as complementors of the ecosystem.

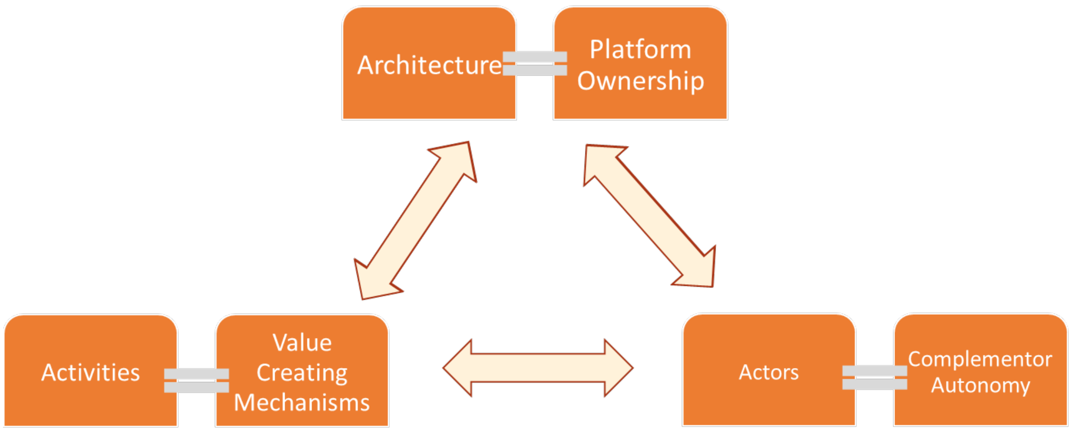

Figure 32: Building Blocks of DPE (own illustration, based on Hein et al. (2019))

10.2 Digital Platform Ecosystem for Reuse

By adopting the intervention strategies proposed by the CLD model in the previous chapter, the structure of a new digital platform ecosystem for enhancing the reuse of building components is proposed in this section. With the help of the figure 33, the structural components of the ecosystem are explained. As discussed in the previous section, it is important to note that the proposed structure is from a non-technical or a commercial point of view. Studying the DPE from a technical perspective is beyond the scope of this research.

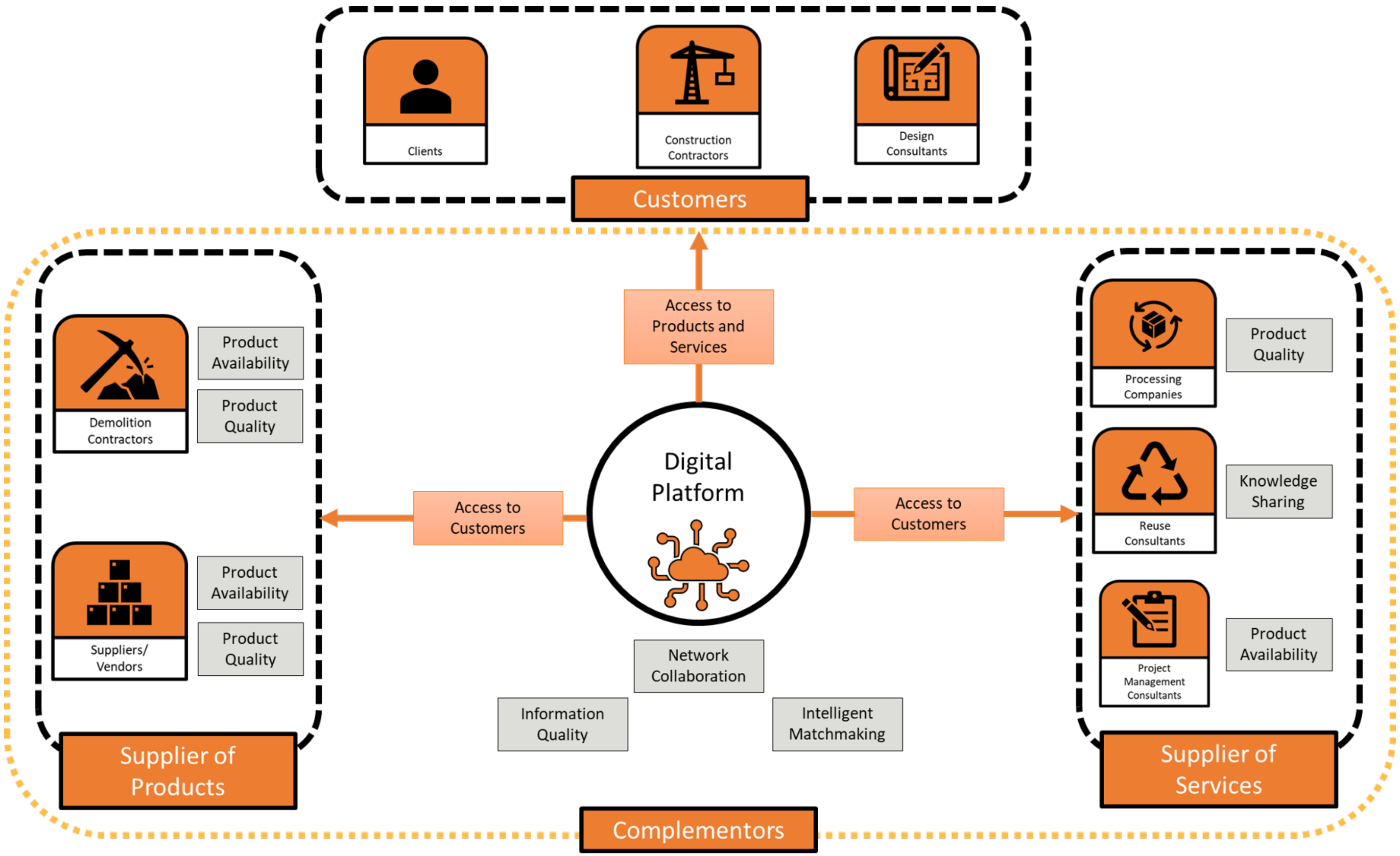

Figure 33: Proposed Digital Platform Ecosystem

Platform Ownership: The anatomy of the proposed DPE constitute the three structural elements as stated before; actors, activities and architecture. The Digital Platform is at the centre of the ecosystem and is surrounded by a set of complementors and customers. The owner of the digital platform has the responsibility of facilitating the value-creating mechanisms. In this case, the values are equivalent to the six intervention strategies corresponding to the reinforcing growth loops derived from the CLD model. These values are expressed in the form of services offered by the ecosystem and are mentioned in the grey coloured boxes of the figure. On the other hand, the complementors are responsible for initiating the actions or activities for creating these values. The complementors in this model are the actors of the system responsible for supplying the products and services to the customer as desired. The role of each complementor and the customer will be explained further while discussing the 'complementory autonomy' block of the ecosystem. The ecosystem is proposed to have a decentralized structure. This implies that the digital platform is not given complete ownership or authority to coordinate the operations within the system. Although the platform owner is the legal owner, every complementor of the ecosystem is given the responsibility to coordinate operations corresponding to the values generated by them. This type of decentralized architecture is explained further in the section 10.2.1 of this chapter.

Value Creating Mechanisms: With the help of the systems thinking approach and the analysis of the CLD model, six intervention strategies were derived. This implies that the DPE should fundamentally be able to offer six services corresponding to these intervention strategies. Based on this thought, the services offered by the complementors of the proposed model are mentioned in the grey boxes. These services correspond to the values generated by the ecosystem. In this case, the digital platform is not given the completer responsibility to generate all the values. The platform needs to add value by facilitating the matchmaking of the suppliers and customers as desired. Besides, it should act as a storage of all the information passing through the platform and be responsible for its moderation and control. Finally, the ecosystem should be able to build a networked structure of all the relevant actors of the system. The remaining values or services are offered indirectly to the customers via the platform. The platform solely acts as a mediator to provide access to the customers in case of complementors and access to the products and services in case of customers.

Complementory Autonomy: As mentioned in the 'platform ownership' block, every complementor of the ecosystem has a significant role to play. Demolition Contractors and Suppliers/Vendors constitute the complementors who are responsible for the supply of recovered building components. Consequently, the services offered by these complementors include 'Product Availability' and 'Product Quality'. Based on the current state of the industry, the product suppliers take up the responsibility of proving the desired services to the customers. Application of ST approach resulted in the generation of new potential services to be offered to the customers which have the possibility to become new business ventures. In this model, services are supplied by three actors or complementors - Processing Companies, Reuse Consultants and Project Management Consultants. The building components recovered from the existing buildings often do not meet the requirements or expectations of the customers. In such cases, the processing companies have an important role to play in facilitating the desired quality of the product. It is significant to note here that processing does not imply recycling; but only to the extent of providing high-value reuse of the recovered component. The next complementor of 'Reuse Consultant' can be a significant spin-off business strategy for several design consultancy firms including the collaborating company of this research, Witteveen+Bos. Integrating recovered building components in the designs desire innovative approaches considering that it has not become a conventional practice yet. Limited knowledge and skills appeared as an important social barrier during the investigation. Thus, experts with sufficient knowledge on the reuse of components can offer their services to the customers. Finally, the 'project management consultants' as a complementor can also be a new business approach. The customers or clients often need to invest additional time and effort to source and procure the right type of product at the right time. The timely availability of desired supply of products is essential for the smooth execution of the project and can be a significant service offered by the complementors.

10.2.1 Proposed Changes

This section discusses in detail the proposed changes with a comparative analysis of the existing digital platforms and pilot programs in the industry. The following four propositions are given to highlight the features of the newly visualized DPE as shown in figure 33.

Proposition 1: Development of a Decentralized Digital Platform Ecosystem

Understanding the distribution of power amongst the actors of a DPE is an important factor during its structural design. As mentioned previously, the authority to define the distribution of power lies within the governing rules proposed by the digital platform owner. The importance of choices of centralized or decentralized governance is emphasized, as platform owners should consider how to balance ownership and power of all sides in the ecosystems based on platform context (Lee et al., 2017). As the name implies, in a centralized ecosystem, the platform owner has all the control power and responsibility. On the contrary, in a decentralized ecosystem, there is a certain distribution of control and responsibilities amongst the actors. With the help of the systems thinking approach and the analysis of the CLD model, six intervention strategies were derived. This implies that the DPE should fundamentally be able to offer six services corresponding to these intervention strategies. Based on this thought, the new model proposes the formation of a 'Decentralized DPE' such that multiple actors or complementors within the ecosystem have the responsibility to effectively offer each service as desired.

Some of the prominent examples of digital tools in the industry as discussed in section 2.2 of Chapter 2 are Madaster, BAMB, Excess Materials Exchange, etc. While there is currently no exclusive study available that defines the type of ecosystems formed by these digital tools, a closer look at the functionalities offered by these platforms point towards centralization, or are focused on offering only one or two services. For example, Madaster is currently focused on providing services in the form of material passports to its users. The platform does not take any ownership of the data. The ownership lies with the users of the platform (like real estate owners), who desire the storage of their product information in the form of material passports. This can be regarded as a form of a decentralized ecosystem. Madaster is responsible only for facilitating the storage and transfer of information. However, the services offered by the platform is focused on only one type, that is, 'information availability'. The CLD model from this research does include 'information quality' as one of the intervention strategies. However, the proposed DPE as shown in the figure 33 above needs several other services corresponding to the remaining intervention strategies. In other words, multiple other complementors can take the responsibility of providing other desired services based on their area of expertise. On the other hand, the structure of the platform 'Excess Materials Exchange' indicates a centralized structure. The platform takes complete ownership of matching the customers to suppliers and also offer consultancy services to indicate the reuse value. Such type of ecosystem is obstructing the entry of other types of actors who can also contribute to the growth of the ecosystem by offering unique services. Thus, the first proposition is to shift from centralization towards a decentralized ecosystem with multiple complementors.

Proposition 2: Shifting to Value-driven ecosystem

The second proposition builds on the idea of exploiting one of the building blocks of any DPE - 'value creating mechanisms'. A successful DPE thrives on facilitating actions that help in generating values for all the actors or complementors in the ecosystem. To begin with, the digital platform can start with executing the intervention strategy of 'intelligent matchmaking'. By facilitating the matchmaking of suppliers and customers, the platform can facilitate the first value of easy accessibility. As can be seen in figure 33 above, the value exchange is not restricted to the suppliers or customers. Based on the number of services offered by each complementor, multiple value streams can be created amongst the actors. This can range from ensuring the desired 'product quality' to facilitating the 'timely availability of product'. Such value-creating mechanisms can eventually lead to the development of a networked structure. Moreover, in this case, it is not just the customers who are benefited from such value-driven ecosystems. For example, a reuse consultant is getting easy access to a pool of customers (eg. architects or designers) who are seeking expertise to decide the reuse potential of building components. Eventually, the reuse consultant firms may invest in developing complementary solutions for the growth of the digital platform. Designing a tool that can automatically calculate the reuse potential of a component is a possibility. Such innovative approaches can lead to the co-creation of additional value-creating mechanisms in the ecosystem.

By again taking the example of existing tools in the industry, it can be observed that these are currently restricting the possibility of additional innovative co-creating mechanisms by the complementors. Currently, the customers of Madaster are being offered only one type of value-creating mechanism - the generation of material passports. In other words, it is obstructing the creation of additional values by other complementors who have unique expertise. When it comes to Excess Materials Exchange, an initial exchange of value is created through matchmaking. There is a possibility to have additional value streams if multiple complementors are given the authority through decentralization. Thus, the proposition of shifting to a value-driven ecosystem is to ensure the growth of the ecosystem through co-creation by multiple complementors.

Proposition 3: Reinforcing Growth Model

One of the fundamental characteristics of a DPE is its generativity. Generativity is defined as the "overall capacity to produce unprompted changes driven by large, varied, and uncoordinated audiences" (Zittrain, 2005). This can be seen as an extension of the previous proposition where complementors come together to co-create and innovate leading to the growth of the ecosystem. From the CLD of this research, it was revealed that the system thrives on a reinforcing growth model where power is generated from one side of the market to the other and vice versa. This is an indication of the generativity of the ecosystem model. Once the initial networked structure of actors within the ecosystem is formed, it is an open playground for all the complementors to initiate and co-create. The decentralized structure of the ecosystem gives the opportunity to a diverse set of complementors to come up with new creative ideas. The intervention strategy of 'knowledge sharing' plays a significant role in increasing generativity.

As discussed in section 2.2 of chapter 2, the majority of the solutions in the industry are oriented towards the development of material passports and a few of them towards waste management. However, these digital solutions are currently restricted to their respective domains of focus. While these platforms may have the potential to grow in future by providing additional functionalities, the growth can be accelerated by adopting generativity. The first step towards generativity is to develop a decentralized ecosystem with multiple complementors to support it. As mentioned in the proposed model, the idea is to not restrict the functionalities with storing and providing information but also look into the possibilities of developing new innovative services to complement the main digital platform.

Proposition 4: High autonomy of the Complementors

Autonomy is a term used in the context of DPE to describe the degree of freedom given to the complementors when co-creating values through the digital platform (Hein et al., 2019). Complementors with low autonomy are tightly coupled to the platform through strategic partnerships (Danneels, 2003). On the other hand, high autonomy complementors are loosely coupled and have the freedom and independence to move to a different platform (Boudreau, 2010). The 'Building Reuse System' as defined in this research is complex and highly interdependent. Moreover, each actor in the system is a unique organization and works towards a different goal. For example, as can be seen in the figure 33 above, a supplier is focused on providing only one type of service, that is, recovered building elements. It forms a relationship with the customers via the digital platform through the value stream of 'products'. On the other hand, a reuse consultant is focused on providing guidance and expertise to the customer. The service provided is different and hence the value stream. A common strategic partnership to bind these organizations with different goals is not feasible. Providing low autonomy to such organizations and enforcing strategic partnerships can restrict the entry of new complementors. Strategic partnerships can work for organizations that are mutually dependent on each other such as Android phone companies and Android app companies. The supply chain surrounding building reuse is still at a nascent stage of development. There are hardly any independent organizations that are focused on the goal of enhancing the reuse of building components in the industry alone. Organizations may not be willing at this stage to engage in such high-risk investments. As stated in propositions 1 and 2, all the complementors may be given the independence and responsibility to co-create and add value to the ecosystem.

By taking the reference of existing digital platforms in the industry, it can be seen that all the platforms focus on forming strategic partnerships with other independent organizations. Consequently, the benefits from the platform are also restricted within this partnership network. To quote an example, demolition contractors have the potential to grow as significant complementors in the ecosystem. Their sole aim is to ensure the sale of recovered building components and extract a profitable amount out of them. They have two choices with them - one is to make their sale through the proposed DPE and the other option is to use their pool of customers to make the sale. If the DPE is working on the principle of low autonomy, an external organization such as the demolition contractor may be hesitant to enter such a restricted network. On the other hand, if given high autonomy, the contractor can experiment within the network of the DPE and has the freedom to switch to a different platform if necessary. Thus, the proposition states that the growth of the ecosystem should not be through closed strategic partnerships but the enhancement of the value chain. Complementors seek the independence to engage in value generation experimentation and hence be given high autonomy.

Chapter 11
System Adaptations

11 System Adaptations

The interpretation of the CLD resulted in the identification of fundamental guiding principles that can aid the development of an ideal digital platform ecosystem. However, as mentioned in Chapter 3, the foundation of a functioning system is largely dependent on its components which include the actors and processes within it. While a digital platform ecosystem can be seen as a tool to streamline the building reuse strategies, these efforts need the active involvement of the actors and the efficiency of the processes. The holistic view achieved through the CLD is also indicative of the fact that the fundamental intervention strategies are initiated by the actors and these have an effect on the processes within the system. This chapter is focused on giving suggestive adaptations that are necessary to implement the intervention strategies. It is essential to point out that the following recommendations must be observed as suggestions or guidelines to aid the system. These recommendations may change depending upon the dynamics involved in the system at a given point of time or a given context.

11.1 Recommendations for Actor adaptations

While defining the systems in Chapter 3, it was mentioned that the two sub-systems are interconnected to each other through their component elements. In the CLD, the actors such as clients, designers, building owners/suppliers, etc., were integrated as key variables. This naturally calls for a redefining of the actor-network and the actor roles. Considering the limitations of the research, it was not possible to thoroughly analyze the role-shift of all the actors in the system. The following section describes the observations based on the interpretation of the CLD.

Actor-Onion Diagram

Onion diagrams are ways of representing stakeholder relationships specific to a project, issue or problem (Leventon et al., 2016). In such diagrams, the centre of the model is used to define the issue or project in which the actors or the stakeholders have a vested interest. This is encircled by the primary stakeholders who are directly associated with the project. These are also called 'direct stakeholders and internal stakeholders'. The next circle in place consist of the secondary stakeholders who are connected with the problem indirectly. This implies that these stakeholders do not work with the project hands-on, but are responsible for facilitating the processes of the project. They are also termed as 'Internal and Indirect' stakeholders. These stakeholders are benefited at some levels and these benefits can take the form of values, money, knowledge, materials, etc. The last circle is used to indicate the wider environment in which the system operates. These stakeholders might not work for the project or the system but have the potential to obstruct the processes within the system if not given due attention. They are also termed as 'External and Indirect' stakeholders. A representative diagram of the onion model is given in figure 34.

In this study, the 'Building Reuse' is placed at the centre of the onion diagram as shown in figure 35. Based on the intervention strategies that are essential to facilitate reuse, the system requires certain adaptations in the type of actors involved, their influence on the problem and the actor roles. While the core design team for the project remains the same, an additional actor role 'Reuse Consultant' is added to the list of primary stakeholders. Additional stakeholders such as 'Waste Management companies', 'Demolition Contractors' and 'Building Owners/Suppliers' are incorporated in this list of 'Internal and Indirect' stakeholders. While these actors cannot directly influence the project decisions; the quality, quantity and availability of the recovered elements largely depend on the effective collaboration with these stakeholders. Finally, the regulatory bodies such as the government, local community and interest groups can influence the choice of materials to assure environmental and health safety. The addition of 'Maintenance Contractor' may be debatable in this case. While discussing a product life cycle, the maintenance contractor has a huge influence on its quality. In addition, they are usually aware of all the changes that a product goes throughout its life cycle. Including the 'maintenance contractor' in the actor-network is deemed essential to achieve the long term goals of reuse in future. The following section gives a summary of the recommendations for 'Actor adaptations'. The researcher does not imply that this is an exhaustive list of actors or the adaptations but are strictly based on the results from the CLD.

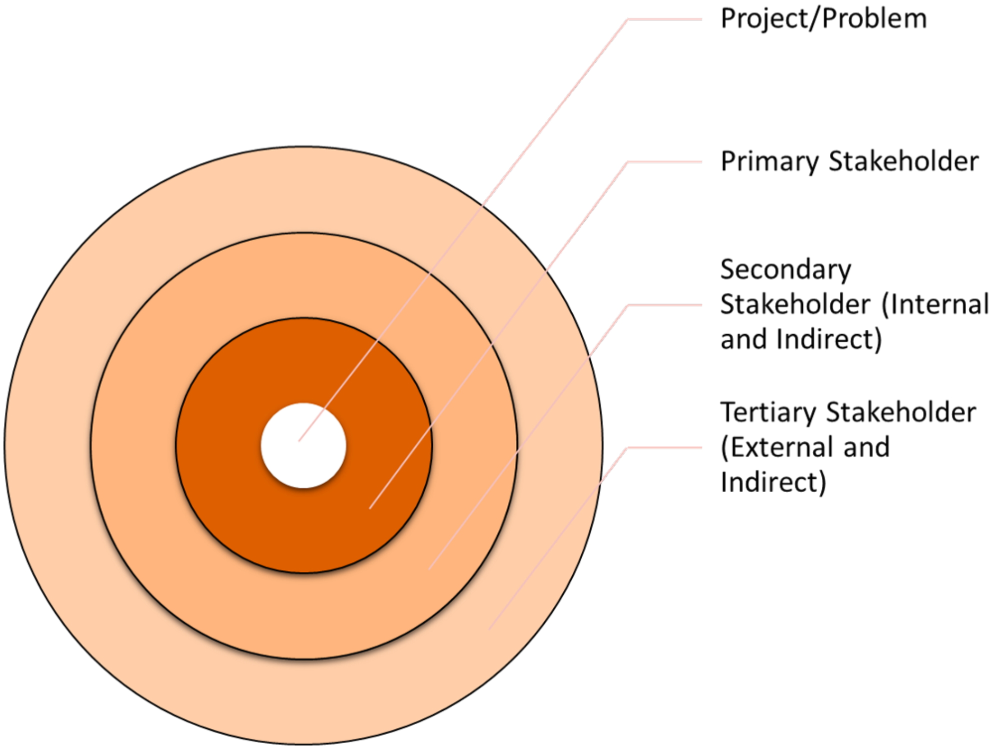

Figure 34: Onion model

New Actor roles: While working with recoverable building elements, there is always an uncertainty concerning the number of available elements, their quality and their timely availability. These uncertainties are one of the major reasons that demotivate the designers to work with reusable elements. Designers are usually required to be extremely flexible with their designs which results in multiple iterations and can eventually impact the design cost. Assigning the responsibilities to verify the availability of elements based on quantity and quality can be extremely daunting for the design team. To improve the efficiency of the design process, the addition of an extra actor role such as the 'Reuse consultant' can be helpful. While the actual procurement of materials happens at a later stage for any construction project, the reuse consultant can assist the design team in making appropriate decisions based on availability. Such adaptations can not only assist in reducing the design iterations but also help in devising efficient sourcing and procurement strategies.

Active Client Involvement: Integrating recovered elements in new projects adds to the project complexities. The client needs to be actively involved throughout the project as every decision concerning the elements can have huge impacts on the project costs, environmental and health impacts, etc. It is essential the client and the design team have a definite consensus on the materials and components to be used. As mentioned before, the amount of flexibility in time and cost plays a significant role that cannot be attained without the client's supports. Besides, as a result of the fragmented nature of the supply chain, the design team is always under the pressure to reserve the elements immediately. In such cases, the client should be able to assure the timely availability of funds to source such elements.

Innovative approach by Designers/Architects: In the current scenario, there are no established guidelines or procedures specific to reuse that can assist the design teams during the process. With the acknowledgement that reuse is an emerging concept, the designers must be willing to innovate, experiment and adapt. This can call for multiple design iterations, development of prototypes or lab-testing. The design team also has the additional responsibility of assuring the quality of the recovered elements. The absence of quality testing procedures can be mitigated if the design teams take the responsibility of devising internal grading and assessment criteria for taking decisions. If working at a project-to-project level, where an entire demolishable building is considered for reuse, the designers may have the additional responsibility of inspecting the quality, structural configuration, type of materials and components, etc., along with the demolition contractors.

Building new Actor relations: The success of the system largely depends on the effective network collaborations amongst all the actors of the system. The clients or the design teams may need to establish new relations with demolition contractors, suppliers, waste management companies, etc. Sourcing and procurement of recovered elements is an enormous responsibility and external expertise may need to be acquired. As discussed in the previous chapter, the digital platform ecosystems can play a huge role in facilitating the establishment of a network.

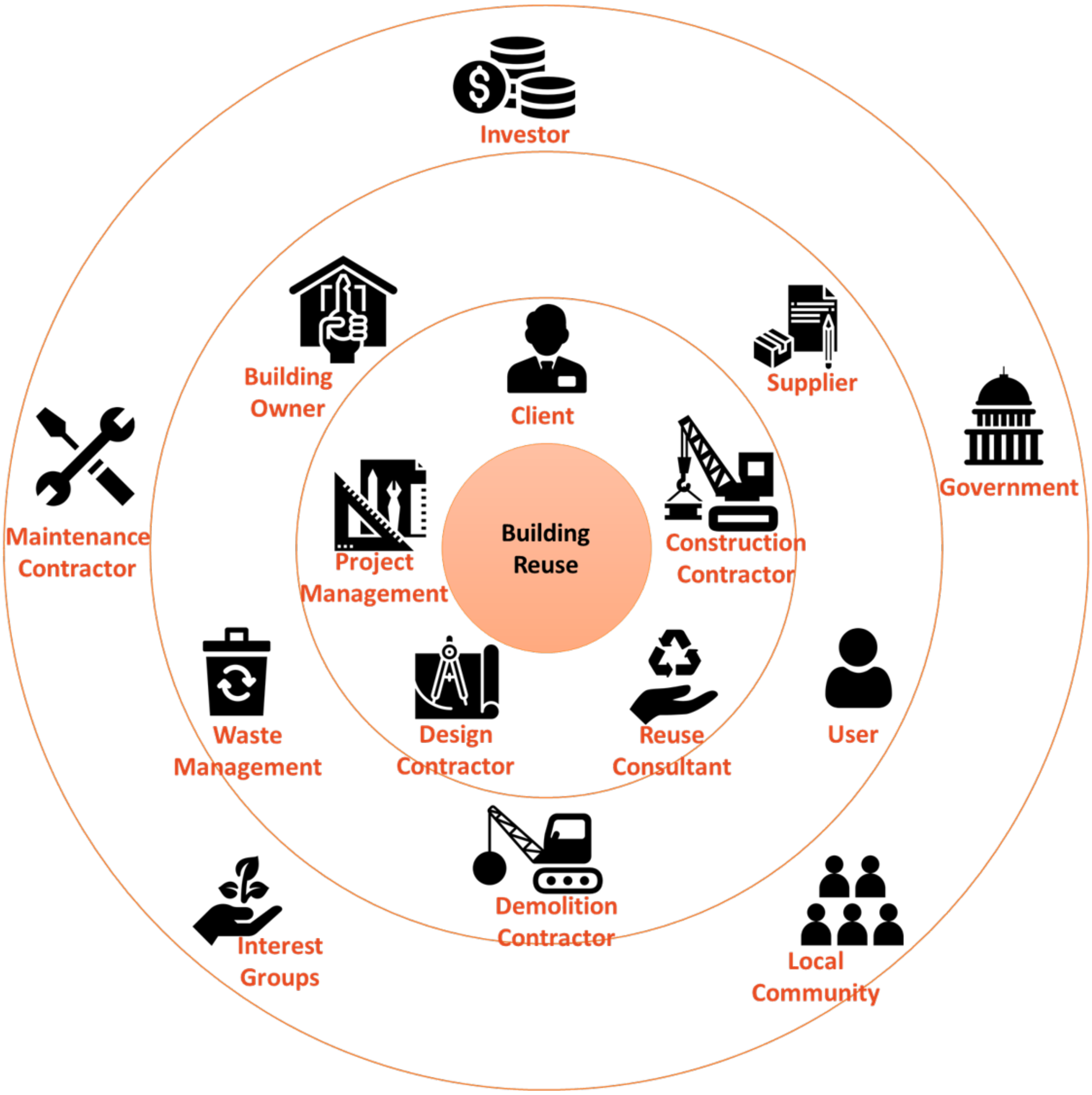

Figure 35: Actor Onion diagram
(The icons used in this figure are taken from www.flaticon.com (*Flaticon* (n.d.)))

11.2 Recommendations for Process adaptations

Integrating recovered elements in a new building project demands a considerable amount of design flexibility. The conventional process of designing might not always work, and it calls for adaptations in the design process. This section is intended to highlight changes that need to be accommodated at a 'bird's eye view' as shown in figure 36. These changes are based on the results from the game session. The number of processes in each phase can be much more detailed in practice. The figure is divided into three rows - the first row shows the four major phases within the 'Building Design Management' sub-system; the second and the third rows indicate the recommended adaptations and their integration with the existing processes. The following paragraphs take the reader through each step of the 'process adaptations' diagram.

Programming phase: This phase begins with defining the client's expectations. While this is a common step in any standard design process, special emphasis must be given to understanding the reuse-specific requirements of the clients. As the concept is not conventional yet, the clients must be informed sufficiently by the design team. There needs to be a mutual agreement on the intended reuse percentage. Based on the client expectations, the design team should internally establish reuse-related goals and objectives. All the involved stakeholders need to be sufficiently informed about the achievable targets of the team. The next step in this phase is the search for existing buildings that are nearing the end of the life cycle and ready to be demolished. Based on the responses from the game, working on a project-to-project level such that the majority of reusable elements are sourced from one particular project was preferred. Thus, this step takes precedence over the search for materials/components from diverse marketplaces. This step is placed in the programming phase as working on a project-to-project level can have significant implications on the contractual obligations. The client and the demolition contractor may have to discuss several factors concerning the quality, quantity and availability of the recoverable building elements. This is especially relevant as the timelines of a building demolition process vary largely as compared to the design phase. Consequently, several other factors such as storage, transportation and processing need to be addressed. Based on these inputs, the deliverable for the programming phase shall be prepared and produced as input for the next phase.

Schematic Design phase: In the 'Schematic Design' phase, only one additional step has been recognized as an adaptation to facilitate reuse. This step is mainly focused on conducting a preliminary search of the existing options of reusable materials and components in the market. This step is placed specifically in the 'schematic design' phase as it does not have any major implications on contractual obligations. Once the designers have narrowed down the preferred options for reuse, the responsibility to source the supply lines with the procurement team. As per the preference of the team players in the game session, working on a project-to-project level is advantageous especially when the reuse of structural components are intended. Nevertheless, both the options can also be adopted simultaneously based on the preferences of the client and design team. Considering that the design needs to be flexible based on the availability of reusable components, multiple iterations of design options are unavoidable.

Detailed Design: The detailed design is considered as a logical extension to the schematic design phase. Two additional steps are recognized in this phase, namely, 'Defining Internal grading and assessment criteria' and 'Life cycle Impact assessment. With the emerging needs of developing sustainable buildings, the step of life cycle impact assessment is already being adopted in the industry. In the case of reuse, this can be considered as a mandatory step as the final decision on the choice of recovered elements is based on the life cycle impact analysis. Life cycle impact assessment needs to be conducted not only for the environmental impact but also for the life cycle costing. If the usage of recovered elements can have detrimental effects on the environment or increase the maintenance cost in the long run, it defeats the purpose of integrating recovered elements. Besides, there are no standard regulations available currently to verify the quality of such building elements. The responsibility may be taken over by the design teams to develop internal criteria which need to be given as input to life cycle impact assessment for taking an informed decision. Above all, as mentioned in the previous phase, multiple iterations might be needed before arriving at the final design.

Construction documentation: The final phase of the design process called the 'Construction Documentation' needs to be kept intact as much as possible. This phase is mainly focused on developing drawings and documents for inviting bidding quotes for contractual work. Any major change to the design at this phase can have a significant impact on the project cost. The next logical step that can also run parallel to this step is the 'Development of Sourcing and Procurement strategies'. Although this step does not usually fall within the scope of the design phase, it has been included in this phase to emphasize that the developed designs may need to undergo changes based on the inputs from the procurement plans. Non-feasible options may have to exclude from the designs.

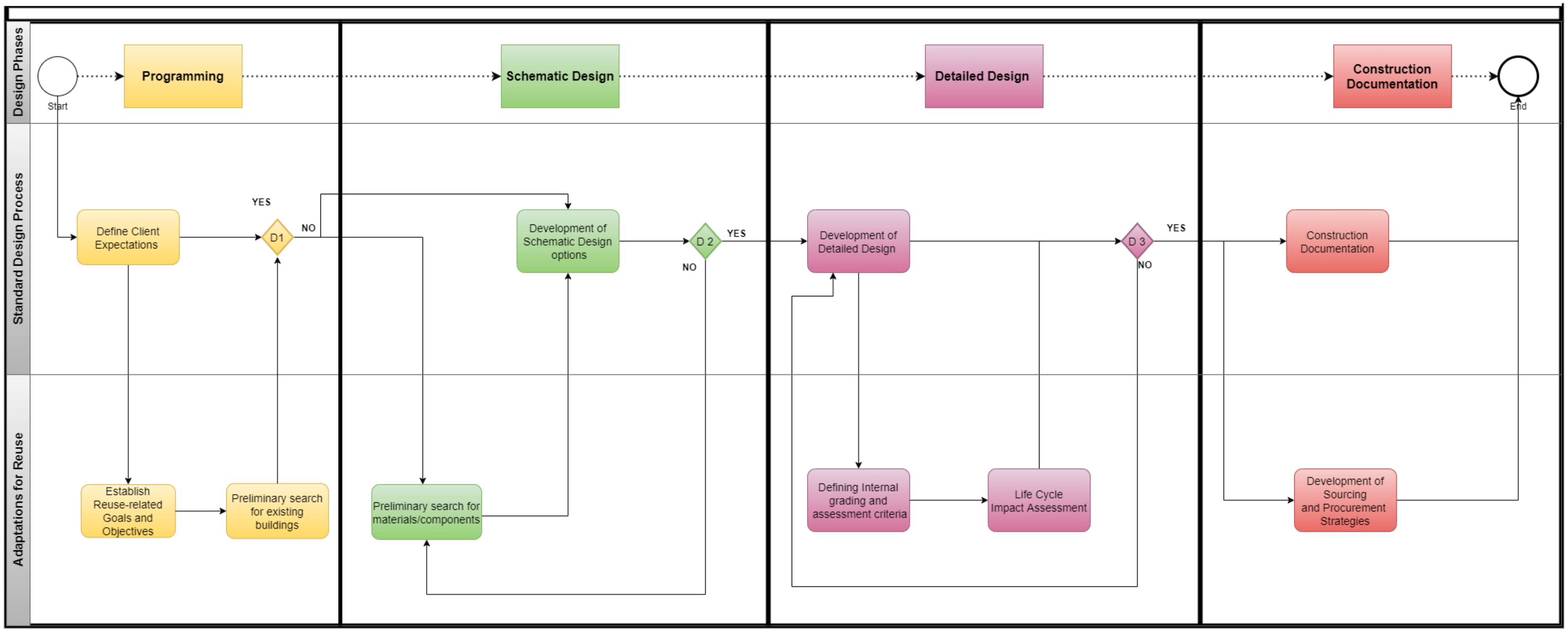

Figure 36: Process Adaptations

Chapter 12 Discussion and Conclusion

12 Discussion and Conclusion

This chapter begins with discussing the contributions made by this research towards academia and industry. This is followed by summarizing the results of this research for every sub-question and finally the main research question. Finally, the research concludes with emphasizing on the limitations of this research which are later used as stimulants for future recommendations.

12.1 Discussion

The Dutch government has established the ambition of transitioning completely into a circular economy by 2050. This ambition has instigated several attempts in the industry as well as academia to develop strategies towards achieving this goal. Based on the findings from the literature study and expert consultation, it was found that the strategies can be broadly classified into two sections when it comes to the construction sector. The first set of strategies are focused specifically on waste management strategies and the other set of strategies are focused on designing for the future. The Dutch construction sector has made significant achievements in waste management by diverting the majority of the waste from landfills to recycling units. The responsibility of waste management currently lies with the demolition industry. On the other hand, designers and architects are developing innovative approaches to design buildings for the future in such a way that these can easily be deconstructed and reused. While both sets of strategies are essential and significant in their ways, an important link connecting these two sets of strategies, that is, high-value direct reuse of recoverable buildings has received less attention. Having said that, it needs to be acknowledged that recovering and integrating reusable elements from existing building stock into new projects is not easy. While the barriers associated with such high-value reuse has been written and established in the literature, the solutions to overcome these barriers are still at a nascent stage of development. In real practice, the high-value reuse of building elements is restricted to a few unique experimental projects. In the problem context and analysis chapter, a detailed discussion on the existing pilot projects in the industry was discussed. The focus of these projects is not solely on the reuse of recoverable building elements, but on establishing a circular construction sector in general. The majority of these pilot programs/projects are focused on capturing maximum possible information about buildings in a digital space and thus, develop centralized repositories for future use. While the relevance of database development cannot be overlooked, this type of building information can facilitate the deconstruction and reuse of buildings in future. However, the real challenge lies in the application of the same type of approach alone towards reuse of components from existing buildings.

The extent of study regarding the reuse of building components has been widely restricted towards understanding the barriers in the industry. A very few literature has attempted to propose solution in this regard and are mostly in the form of recommendations at large. In addition, certain studies have focused on proposing a solution towards one particular aspect of the reuse such as economic or technical. An attempt towards proposing a holistic solution to the issue has not been discussed yet. This research proposes the idea of combining three schools of thoughts - Systems Thinking theory, Digital Platform Ecosystems and Reuse, to propose a solution towards enhancing reuse. Systems thinking is not a new concept and has found significant applications in the industry. As has been mentioned before, it calls for the need to develop a holistic perspective towards problems. It acknowledges that problems in a system are complex and the right approach towards solving such issues is by embracing complexity. The majority of the issues observed in any industry are part of a system and analyzing them with a systems thinking tool can help in generating interesting insights. In this research, the CLD was developed based on the inputs from experts involved in the design of projects. However, the tool enables the researcher to get to the root cause of technical problems in the design process, which often lies in another dimension, and thus, get a holistic picture of the system. Having said that, the outputs from the diagram analysis may vary based on the inputs from a different set of experts. To exploit this approach to the fullest, business developers, management consultants, project managers, clients, suppliers, etc. must contribute equally to the model. Nevertheless, this research was able to analyze the system of building reuse from a holistic perspective which revealed the loci of possible improvements.

The intervention strategies proposed in this research are based on the exploitation of the functions provided by a digital platform ecosystem. Digital platform ecosystems, if developed with proper business strategies, can lead to the formation of a well-established network. Thus, the results from the systems thinking approach were further extended to analyze their implications on the industry. A possible structure of a new DPE was proposed in this research. This structure is not completely oblivious to the digital solutions of the industry. Instead, the model focuses on building upon the existing digital platforms. The propositions of change in the newly visualized structure of the ecosystem focuses majorly on creating an open and decentralized system. It encourages multiple actors in the industry to innovate and co-create leading to the development of new potential business ventures. The model proposes to take advantage of the networked structure of actors created within a DPE and grow exponentially.

12.2 Conclusions

The research aimed to address the issue of missing a holistic approach towards developing a digital platform focused on enhancing the reuse of recovered building elements. This section focuses on summarizing the conclusions for each sub-question and then finally collating them to answer the main research question.

SQ1: What are the barriers responsible for restraining the reuse of recoverable building components from existing buildings?

The reuse of recoverable building components as a replacement for raw materials in new construction projects is not easy. Several barriers are associated with it and have been studied extensively in the literature. As this research is ultimately relying on drawing solutions by addressing the root cause of this problem, it was essential to highlight the most important barriers. These identified barriers are summarized below:

- **Economic barriers:** Cost is considered to be the most important reason for the demolition contractors and designers to not adopt reuse in practical cases. The deconstruction techniques have not been fully automated yet and the involvement of manual labour adds to the cost. Consequently, the cost of the final recovered component shoots above the cost of raw materials discouraging the demand industry to adopt it as their first preference.

- **Technical barriers:** The existing buildings which are already nearing the end of the life cycle have highly complex designs and are not suitable for easy deconstruction. Besides, these old buildings do not have sufficient documents to produce information adding complexity. When it comes to the designers, the technical barriers were not seen to be a major problem. Through innovative approaches, the technical barriers can be addressed to a huge extent.

- **Regulatory barriers:** The governmental organizations have a huge role to play in standardizing and regulating the implementation of reuse in the industry. Currently, there are no regulations that distinguish reuse from recycling which is adding to the lack of clarity. Besides, the absence of quality testing and approval procedures is adding to the negative perceptions revolving around the usage of recovered elements.

- **Environmental and Safety barriers:** As mentioned before, there are no regulations currently that can adequately test the recovered elements for their environmental impacts. Besides, deconstruction involves a lot of manual labour and the health of labourers is a major concern. These factors restrict the reliability of the recovered elements and consequently their acceptability.

- **Organizational barriers:** These barriers are prominent on the side of the demand industry. The integration of recovered elements in new projects requires high flexibility and the willingness to take risks. As a result, there is a lack of initiatives from the client-side to support the design teams in experimenting with such projects.

- **Social barriers:** The negative perception of the stakeholders towards the usage of recovered elements is one of the major social barriers. The poor visual appearance accompanied by the absence of quality test certificates affects their large scale acceptability.

SQ2: What are the key drivers of change affecting the design process of building projects involving the reuse of recoverable elements?

The key drivers of change were derived based on the inputs from the experts in the industry. These can be summarized as given below. Besides, implications of these key drivers in industrial practice were used to develop project scenarios which were represented in the game model of next phase.

- Improving Economic Feasibility

- Active involvement of Clients and Designers
- Improved and adapted Building Information Database
- Established Supply market
- Improved collaboration and active interventions
- Innovative approaches to ensure technical feasibility

SQ3: How can a simulated model of the 'Building Reuse' system be developed using a serious gaming approach?

A simulated model in the form of an online board game was designed to represent the conditions of a 'Building Reuse' system. The ultimate aim of this game was to derive the key variables that affect the dynamics of the system. These key variables were used as input to develop the CLD in the next phase of the research. In total, 45 different variables were derived and are listed in the table 9 of Appendix.

SQ4: How can a Causal Loop Diagram (Systems Thinking tool) be developed to synthesize the fundamental guiding principles of the desired digital platform ecosystem based on the results from the game?

By connecting the 45 key variables from the previous phase, based on their inter-relationships, the CLD was developed which contains a total of 10 feedback loops as seen in figure 20. Among these feedback loops, 6 loops are reinforcing loops which are indicated with brightly coloured circles and 'R' at the center. The relationship arrows are given similar colors to show the connected variables corresponding to the loops. While the remaining 4 loops are balancing loops indicated with hexagons and 'B' at the center. The diagram revealed that the system is based on a series of reinforcing feedback loops that reinforce the power from the demand side of the market to the supply side and vice versa. Ideally, implementation of the intervention strategies corresponding to these reinforcing feedback loops should guarantee an exponential growth of the platform ecosystem. However, upon critically analyzing the diagram revealed that the platform cannot attain an ever increasing growth with the application of these strategies. The CLD contains 4 balancing loops which can lead to the collapse of the model and must be given special attention while designing the platform.

Main Research Question: How can the systems thinking approach be used to develop a digital platform ecosystem for facilitating the design of new buildings with recoverable building components from existing buildings?

In conclusion, this research demonstrated the application of ST as a problem-solving approach to enhance the reuse of recovered building elements in new construction projects. Enhancing the reuse of building elements is a complex problem with several layers and multiple dimensions. Most of the existing solutions in the industry focus on developing individual products and tools. This is a reductionist approach where complex problems are broken down into smaller issues and solutions are developed to solve each issue. However, ST theory proposes to go the other way round and advises to embrace the complexity. The holistic approach revealed the interrelationships and dependencies of all the elements within the 'Building Reuse System' which are not otherwise addressed in a reductionist approach. Besides, the research proposes to exploit the advantages of a digital platform ecosystem. Digital platform ecosystems focus on developing a business model with digital technologies as the lifeline. Large scale acceptance of recovered elements is possible when this issue is addressed as a complex business problem. It requires fundamental changes in the existing business models, supply chain networks and social outlook. Commercialization of the business by exploiting the digital platform is proposed as an informed way to move forward. Thus, the research tries to fuse three different schools of thought, namely, Systems Thinking, Reuse and Digital platform ecosystem.

The CLD is an important tool in the ST approach that gives a holistic perspective of the problem at hand. Although it can be seen as a mere visualization tool at first, adoption of the model development process followed by its critical analysis can reveal several leverage points. These leverage points indicate the locus points of the system that needs attention and can decide the success or failure of the entire system based on how they are addressed. The research was concluded by proposing 10 intervention strategies that can be adopted as fundamental guiding principles while developing a digital platform ecosystem. Each intervention strategy is accompanied by minimum requirements criteria that need to be fulfilled while adopting the strategies. The intervention strategies are proposed by recognizing the strengths of digital platform ecosystems. By building on these intervention strategies, four propositions of change were given by comparing the existing scenario of the industry to the desired structure of a digital platform ecosystem. The propositions are enlisted below:

- Proposition 1: Development of a Decentralized Digital Platform Ecosystem
- Proposition 2: Shifting to Value-drive ecosystem
- Proposition 3: Creating a Reinforcing Growth model
- Proposition 4: High autonomy of the Complementors

To assist these propositions, the structure of a possible DPE is described along with a diagrammatic representation as shown in figure 33. The research is concluded with the acknowledgement that implementation of the intervention strategies will require certain adaptations in the system. A conclusive, but not exhaustive list of recommended adaptations in the design process and actor-network is provided to accompany the interventions strategies.

12.3 Limitations

This section is used to draw the reader's attention to the limitations associated with the research. These limitations shall be discussed further in section 12.4, where recommendations to overcome these limitations as a future research opportunity are given. The limitations are as follows:

- CLD that was developed to visualize the 'Building Reuse System' as a whole was predominantly based on the inputs from the actors of only one of the sub-systems - 'Building Design Management system'. Besides, these actors represented only the design team under this system. In real practice, several other stakeholders are associated with this problem and larger data sample is essential to generate multiple other leverage points and corresponding intervention strategies.
- The CLD was developed and analyzed by the researcher alone. If the model was developed by other researchers or in consultation with other stakeholders of the industry, it could have revealed multiple other patterns and leverage points.
- The final phase of the proposed research methodology framework deals with the implementation of the proposed intervention strategies. As the research was undertaken as part of the an academic thesis, several limitations concerning time and resources had to be taken into consideration. Thus, the research was concluded with the proposal of certain changes to the existing approach in the industry. Testing the validity of the strategies through implementation remains a limitation.
- The ST approach recognizes that systems are highly dynamic. Depending upon the changes in time and external environment of the system, the inter-relationships amongst the variables can change. Although this can be seen as an advantage of the method to embrace complexity, it can seem to be chaotic for the practitioners.
- The scope of this research is limited to the boundaries of the system defined for this study. Thus, it has not accommodated other phases of a building project such as construction, operation, maintenance and use phase.

12.4 Future Recommendations

This section is focused on proposing future research possibilities to overcome the above-mentioned limitations of this research. The future recommendations are as follows:

- The CLD may be developed further by taking inputs from multiples stakeholders associated with the problem. Validation of the existing model revealed that larger importance is attached to the technical and economic barriers of reuse. The sample of experts can be extended to ensure that there is equal important attached to each type of barrier. Besides. multiple researchers may develop such models and these can be cross-verified to avoid irregularities.

- The four propositions based on the intervention strategies identified in this research can be evaluated through experimentation. Development of experimental digital platform ecosystems along the lines of 'living labs' is a possible way of validation.
- The variables and their inter-relationships of a CLD model can be converted to mathematical equations and these can be analyzed numerically to reveal concrete patterns. Such quantitative analysis can provide better control on the system dynamics. Platforms such as 'Vensim' offers tool to facilitate such analysis.
- The life cycle of any building element is not restricted between the two sub-systems defined in this research - deconstruction and design systems. The research can be further extended by taking into consideration different phases of a building life cycle.

References

About Platform CB'23. (n.d.). Retrieved from `https://platformcb23.nl/over-platform-cb-23`

Adner, R. (2017). Ecosystem as Structure: An Actionable Construct for Strategy. *Journal of Management*, *43*(1), 39–58. doi: 10.1177/0149206316678451

Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling*, *102*. doi: 10.1016/j.resconrec.2015.06.001

Ali, A. K., Badinelli, R., & Jones, J. R. (2013). Re-Defining the Architectural Design Process through Building a Decision-Support Framework for Design with Reuse. *The International Journal of Sustainability Policy and Practice*, *8*(1), 1–18. doi: 10.18848/2325-1166/cgp/v08i01/55385

Allen Will. (n.d.). *Systems thinking - Learning for Sustainability.* Retrieved from `https://learningforsustainability.net/systems-thinking/`

Asadullah, A., Faik, I., & Kankanhalli, A. (2018, 7). Digital Platforms: A Review and Future Directions..

Barlas, Y. (1996). *Formal aspects of model validity and validation in system dynamics* (Tech. Rep.).

Benachio, G. L. F., Freitas, M. d. C. D., & Tavares, S. F. (2020). *Circular economy in the construction industry: A systematic literature review* (Vol. 260). doi: 10.1016/j.jclepro.2020.121046

Bertin, I., Lebrun, F., Braham, N., & Le Roy, R. (2019, 9). Construction, deconstruction, reuse of the structural elements: The circular economy to reach zero carbon. In *Iop conference series: Earth and environmental science* (Vol. 323, p. 012020). Institute of Physics Publishing. Retrieved from `https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012020https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012020/meta` doi: 10.1088/1755-1315/323/1/012020

Bertin, I., Mesnil, R., Jaeger, J. M., Feraille, A., & Le Roy, R. (2020, 4). A BIM-based framework and databank for reusing load-bearing structural elements. *Sustainability (Switzerland)*, *12*(8), 3147. Retrieved from `www.mdpi.com/journal/sustainability` doi: 10.3390/SU12083147

Boudreau, K. (2010, 7). Open Platform Strategies and Innovation: Granting Access vs. Devolving Control. *Management Science*, *56*, 1849–1872. doi: 10.1287/mnsc.1100.1215

Cavana, R., & Maani, K. (2000). *A Methodological Framework for Systems Thinking and Modelling (ST&M) Interventions.* (Tech. Rep.). Retrieved from `https://www.researchgate.net/publication/221503119_A_Methodological_Framework_for_Systems_Thinking_and_Modelling_STM_Interventions`

Chan, P. W., De Wolf, C., & Koutamanis, A. (n.d.). The digital potential in creating a circular construction economy. Retrieved from `https://doi.org/10.3390/buildings8110150.`

Chinda, T., & Ammarapala, V. (2016). Decision-making on reverse logistics in the construction industry. *Songklanakarin Journal of Science and Technology*, *38*(1).

The Circular economy - AkzoNobel Report. (2015). Retrieved from `https://report.akzonobel.com/2015/ar/case-studies/the-circular-economy.html`

Cornet, S. M., den Berg, v. M., & Oorschot JAWH, v. (2016). *D1 Synthesis of the state-of-the-art Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system* (Tech. Rep.).

Crookall, D. (2010, 12). *Serious games, debriefing, and simulation/gaming as a discipline* (Vol. 41) (No. 6). SAGE PublicationsSage CA: Los Angeles, CA. Retrieved from `http://sg.sagepub.com` doi: 10.1177/1046878110390784

Danneels, E. (2003, 6). Tight–loose coupling with customers: the enactment of customer orientation. *Strategic Management Journal*, *24*(6), 559–576. Retrieved from `https://onlinelibrary.wiley.com/doi/full/10.1002/smj.319https://onlinelibrary.wiley.com/doi/abs/10.1002/smj.319https://onlinelibrary.wiley.com/doi/10.1002/smj.319` doi: 10.1002/SMJ.319

DEMOLITION FIRST ERASMUS MC BUILDING - Madaster. (2018). Retrieved from https://madaster.com/demolition-first-erasmus-mc-building/

Densley Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, *148*. doi: 10.1016/j.jclepro.2017.02.006

Design to Construction | AIA ETN. (n.d.). Retrieved from https://www.aiaetn.org/find-an-architect/design-to-construction/

Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Cullen, J. M., & Allwood, J. M. (2018). Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain. *Journal of Cleaner Production*, *183*. doi: 10.1016/j.jclepro.2018.02.141

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2020). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*. Retrieved from https://www.tandfonline.com/action/journalInformation?journalCode=taem20 doi: 10.1080/17452007.2020.1781588

European Commission. (2019). Supporting digitalisation of the construction sector and SMEs Including Building Information Modelling. Retrieved from http://www.europa.eu doi: 10.2826/422658

Excess Materials Exchange. (2019). *PILOT REPORT* (Tech. Rep.).

Excess Materials Exchange. (n.d.). Retrieved from https://excessmaterialsexchange.com/en_us/

Flaticon. (n.d.). Retrieved from https://www.flaticon.com/

Forrester, J. W., & Senge, P. M. (1980, 7). Tests for building confidence in system dynamics models." System dynamics. TIME studies in the management science. *A. A. Legasto, Jr., J. W. Forrester, and J. M. Lyneis, eds.*, *14*, 209–228.

Foundation, E. M. (2013). *Ellen Mcarthur Foundation* (Tech. Rep.).

Gawer, A., & Cusumano, M. (2014, 7). Industry Platforms and Ecosystem Innovation. *Journal of Product Innovation Management*, *31*. doi: 10.1111/jpim.12105

Ginga, C. P., Ongpeng, J. M. C., & Daly, M. K. M. (2020, 7). *Circular economy on construction and demolition waste: A literature review on material recovery and production* (Vol. 13) (No. 13). MDPI AG. doi: 10.3390/ma13132970

Göbel, S. (2016). Serious Games Application Examples. In *Serious games* (pp. 319–405). Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-40612-1_12 doi: 10.1007/978-3-319-40612-1{_}12

Gorgolewski, M. (2008). Designing with reused building components: Some challenges. *Building Research and Information*, *36*(2). doi: 10.1080/09613210701559499

Gorgolewski, M. (2019). The architecture of reuse. In *Iop conference series: Earth and environmental science* (Vol. 225). doi: 10.1088/1755-1315/225/1/012030

Gorgolewski, M., & Morettin, L. (2009). The process of designing with reused building components. *CMS 2009: Conference on Construction Material Stewardship - Lifecycle design of buildings, systems and materials*.

Guerra, B. C., Leite, F., & Faust, K. M. (2020, 10). 4D-BIM to enhance construction waste reuse and recycle planning: Case studies on concrete and drywall waste streams. *Waste Management*, *116*, 79–90. doi: 10.1016/j.wasman.2020.07.035

Habert, G., & Schlüter, A. (2016). *Expanding boundaries : systems thinking in the built environment : Sustainable Built Environment (SBE) Regional Conference Zurich.*

Haraldsson, H. V. (2004). *Introduction to System Thinking and Causal Loop Diagrams.* Retrieved from www.planteco.lu.se

Harteveld, C. (2011). *Triadic game design: Balancing reality, meaning and play.* Springer London. Retrieved from https://research.tudelft.nl/en/publications/triadic-game-design-balancing-reality-meaning-and-play doi: 10.1007/978-1-84996-157-8

Hein, A., Schreieck, M., Wiesche, M., Böhm, M., & Krcmar, H. (2019, 12). The emergence of native multi-sided platforms and their influence on incumbents. *Electronic Markets*, *29*(4), 631–647. doi: 10.1007/s12525-019-00350-1

Herczeg David McKinnon Leonidas Milios, M., & Klaassens Katarina Svatikova Oscar Widerberg Rotterdam, E. (2014). *Resource efficiency in the building sector Final report Client: DG Environment* (Tech. Rep.). Retrieved from www.ecorys.nl

HISER Project | Novel harmonized methodological solutions and tools. (n.d.). Retrieved from http://www.hiserproject.eu/index.php/our-goals/novel-harmonized-methodological-solutions-and-tools

H. Meadows, D. (2009). *Thinking in Systems* (Tech. Rep.). London: Earthscan.

Hobbs, G., & Adams BRE, K. (2017, 6). *International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste Reuse of building products and materials-barriers and opportunities* (Tech. Rep.). Delft: Delft University of Technology. Retrieved from http://ec.europa.eu/growth/sectors/construction/product-regulation/

Home - Madaster. (n.d.). Retrieved from https://madaster.com/

Honic, M., Kovacic, I., & Rechberger, H. (2019). IOP Conference Series: Earth and Environmental Science Concept for a BIM-based Material Passport for buildings Recent citations Concept for a BIM-based Material Passport for buildings.
doi: 10.1088/1755-1315/225/1/012073

Hopkinson, P., Zils, M., Hawkins, P., & Roper, S. (2018). Managing a Complex Global Circular Economy Business Model: Opportunities and Challenges. *California Management Review*, *60*(3). doi: 10.1177/0008125618764692

Hosseini, M. R., Rameezdeen, R., Chileshe, N., & Lehmann, S. (2015, 6). Reverse logistics in the construction industry. *Waste Management and Research*, *33*(6), 499–514. doi: 10.1177/0734242X15584842

Kamal Ali, A. (2013). *Between Design Process and Process Design: Integrating Reuse Decisions Into Design Process.* Retrieved from https://www.researchgate.net/publication/303894217_Between_Design_Process_and_Process_Design_Integrating_Reuse_Decisions_Into_Design_Process

Kapoor, R. (2018, 10). Ecosystems: broadening the locus of value creation. *Journal of Organization Design 2018 7:1*, *7*(1), 1–16. Retrieved from https://link.springer.com/articles/10.1186/s41469-018-0035-4https://link.springer.com/article/10.1186/s41469-018-0035-4 doi: 10.1186/S41469-018-0035-4

Kibert, C. J., Chini, A. R., & Rinker Sr, M. (2000). *Overview of Deconstruction in Selected Countries CIB, International Council for Research and Innovation in Building Construction Task Group 39: Deconstruction Center for Construction and Environment* (Tech. Rep.). Retrieved from http://s14.cfaa.ufl.edu/centers/sustainable/

Kim, D. H. (n.d.). *What Is Systems Thinking?* (Tech. Rep.). Retrieved from www.pegasuscom.com

Kirchherr, J., Reike, D., & Hekkert, M. (2017). *Conceptualizing the circular economy: An analysis of 114 definitions* (Vol. 127). doi: 10.1016/j.resconrec.2017.09.005

Klinglmair, M., & Fellner, J. (2010, 8). Urban mining in times of raw material shortage: Copper management in Austria during World War I. *Journal of Industrial Ecology*, *14*(4), 666–679. doi: 10.1111/j.1530-9290.2010.00257.x

Leden | VERAS bouwt aan slopen. (n.d.). Retrieved from https://www.sloopaannemers.nl/leden/

Lee, S. U., Zhu, L., & Jeffery, D. R. (2017). Design Choices for Data Governance in Platform Ecosystems: A Contingency Model. *CoRR*. Retrieved from http://arxiv.org/abs/1706.07560

Leventon, J., Fleskens, L., Claringbould, H., Schwilch, G., & Hessel, R. (2016, 9). An applied methodology for stakeholder identification in transdisciplinary research. *Sustainability Science*, *11*(5), 763–775. Retrieved from `http://link.springer.com/10.1007/s11625-016-0385-1` doi: 10.1007/s11625-016-0385-1

Macozoma, D. S. (2001). *Building Deconstruction CIB/CSIR 2001 2 INTERNATIONAL REPORT Prepared for: International Council for Research and Innovation in Building and Construction (CIB)* (Tech. Rep.).

Madaster. (2021, 5). *Madaster Release Notes* (Tech. Rep.). Retrieved from `https://docs.madaster.com/files/en/Madaster%20Release%20notes%202021.pdf`

Mclucas, A., Mclucas, A. C., Ryan, M. J., & Chan, K. M. (2012). *On the Validation of System Dynamics Models Experimental investigation of dynamic decision making using stock and flow problems View project INCOSE Requirements Working Group View project On the Validation of System Dynamics Models* (Tech. Rep.). Retrieved from `https://www.researchgate.net/publication/270163041`

Michael, D. (2005). *Serious Games : Games That Educate, Train, and Inform* (Tech. Rep.). Retrieved from `http://site.ebrary.com/lib/drexel/Doc?id=10087000&ppg=1`

Michael Polina. (2018). *Circular Demolition Process (Master Thesis)* (Unpublished doctoral dissertation). Technische Universiteit Delft, Delft.

Miu, I. (2020). *Fundamental Characteristics and Concept of Material Passports* (Tech. Rep.).

Monat, J. P., & Gannon, T. F. (2015). What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *American Journal of Systems Science*, *2015*(1), 11–26. Retrieved from `http://resources21.org/cl/files/project264_5674/Overv` doi: 10.5923/j.ajss.20150401.02

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*. doi: 10.1016/j.resconrec.2019.104553

Ng, K. S., Yang, A., & Yakovleva, N. (2019, 8). Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK. *Journal of Cleaner Production*, *227*, 248–262. doi: 10.1016/j.jclepro.2019.04.136

Osmani, M. (2012). Construction Waste Minimization in the UK: Current Pressures for Change and Approaches. *Procedia - Social and Behavioral Sciences*, *40*. doi: 10.1016/j.sbspro.2012.03.158

Over ons - Cirkelstad. (n.d.). Retrieved from `https://www.cirkelstad.nl/over-ons-2/`

Pereira Roders, A., Post, J., & Erkelens, P. (2005). *INNOVATING BUILT HERITAGE: ADAPT THE PAST TO THE FUTURE* (Tech. Rep.).

Rakhshan, K., Morel, J. C., Alaka, H., & Charef, R. (2020). *Components reuse in the building sector – A systematic review* (Vol. 38) (No. 4). doi: 10.1177/0734242X20910463

Rameezdeen, R., Chileshe, N., Hosseini, M. R., & Lehmann, S. (2016, 7). A qualitative examination of major barriers in implementation of reverse logistics within the South Australian construction sector. *International Journal of Construction Management*, *16*(3), 185–196. doi: 10.1080/15623599.2015.1110275

Reduce, Reuse, Recycle and Recover Waste: A 4R's Guide (Tech. Rep.). (2008).

Rinker Sr, M. (2005). *Deconstruction and Materials Reuse-an International Overview CIB Publication 300 Final Report of Task Group 39 on Deconstruction Powell Center for Construction and Environment* (Tech. Rep.). Retrieved from `www.cce.ufl.edu/affiliations/cibhttp://www.cce.ufl.edu/`

Rose, C. M., & Stegemann, J. A. (2018). From waste management to component management in the construction industry. *Sustainability (Switzerland)*, *10*(1). doi: 10.3390/su10010229

Ruby, I. e., & Ruby, A. e. (2010). *The cook, the prospector, the nomad and their architect - Re-inventing Construction* (Tech. Rep.). Retrieved from `http://www.holcimfoundation.org`

Sansom, M., & Avery, N. (2014). Briefing: Reuse and recycling rates of UK steel demolition arisings. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, *167*(3). doi: 10.1680/ensu.13.00026

Sawhney, A., & Odeh, I. S. (2020, 2). Digital ecosystems in the construction industry—current state and future trends. In *Construction 4.0* (pp. 42–61). Routledge. doi: 10.1201/9780429398100-3

Schut, E., Crielaard, M., & Mesman, M. (2015). *Circular economy in the Dutch construction sector A perspective for the market and government Status Final* (Tech. Rep.).

Shrubsole, C. (2018, 4). *Systems thinking in the built environment: Seeing the bigger picture, understanding the detail* (Vol. 27) (No. 4). SAGE Publications Ltd. Retrieved from `www.ucl.ac.uk/bart` doi: 10.1177/1420326X18766131

Skjott Linneberg, M., & Korsgaard, S. (2019, 6). Coding qualitative data: a synthesis guiding the novice. *Qualitative Research Journal*, *19*(3), 259–270. doi: 10.1108/QRJ-12-2018-0012

Sterman, J. (2014). *Business Dynamics, System Thinking and Modeling for a Complex World Climate Interactive and the C-ROADS Simulation View project Dynamic Models for Population (Routine) Screening: Understanding Long Term Trends in Policy Decisions of Clinical Practice Guidelines View project* (Tech. Rep.). Retrieved from `https://www.researchgate.net/publication/44827001`

Susi, T., & Johannesson, M. (2007, 5). *Serious Games-An Overview* (Tech. Rep.). School of Humanities and Informatics University of Skövde, Sweden. Retrieved from `www.americasarmy.com;`

Systems and the circular economy. (n.d.). Retrieved from `https://www.ellenmacarthurfoundation.org/explore/systems-and-the-circular-economy`

Tatiya, A., Zhao, D., Syal, M., Berghorn, G. H., & LaMore, R. (2018). Cost prediction model for building deconstruction in urban areas. *Journal of Cleaner Production*, *195*. doi: 10.1016/j.jclepro.2017.08.084

Tingley, D. D., & Davison, B. (2011). Design for deconstruction and material reuse. In *Proceedings of institution of civil engineers: Energy* (Vol. 164). doi: 10.1680/ener.2011.164.4.195

Viva, L., Ciulli, F., Kolk, A., & Rothenberg, G. (2020, 9). Designing Circular Waste Management Strategies: The Case of Organic Waste in Amsterdam. *Advanced Sustainable Systems*, *4*(9), 2000023. Retrieved from `https://doi.org/10.1002/adsu.202000023` doi: 10.1002/adsu.202000023

Waste prevention and management - Environment - European Commission. (n.d.). Retrieved from `https://ec.europa.eu/environment/green-growth/waste-prevention-and-management/index_en.htm`

What Is an Open System? (Tech. Rep.). (n.d.). Authenticity Consulting, LLC. Retrieved from `http://www.authenticityconsulting.com`

Ye, G., Priem, R., & Alshwer, A. (2012, 7). Achieving Demand-Side Synergy from Strategic Diversification: How Combining Mundane Assets Can Leverage Consumer Utilities. *Organization Science*, *23*. doi: 10.2307/41429027

Yeung, J., Walbridge, S., & Haas, C. (2015). The role of geometric characterization in supporting structural steel reuse decisions. *Resources, Conservation and Recycling*, *104*. doi: 10.1016/j.resconrec.2015.08.017

Yiling, F., Weili, Z., & Qiaosong, J. (2019). Evolution of digital platform-based ecosystem: A theoretical framework.
doi: 10.25236/icsm.2019.022

Zagonel, A. A. (2006). *Levels of Confidence in System Dynamics Modeling: A Pragmatic Approach to Assessment of Dynamic Models* (Tech. Rep.). Retrieved from `https://www.researchgate.net/publication/241911743`

Zittrain, J. (2005, 7). The Generative Internet. *Harvard Law Review*, *119*.

Appendix

A Important terminologies and definitions

The following definitions are taken from the article 'Introduction to Systems Thinking' by Daniel H. Kim (Kim, n.d.).

- **Systems Thinking:** A school of thought that focuses on recognizing the interconnections between the parts of a system and synthesizing them into a unified view of the whole.
- **Causal Loop Diagram (CLD):** One of the 10 tools of systems thinking. Causal loop diagrams capture how variables in a system are interrelated. A CLD takes the form of one or more closed loops that depict cause-and-effect linkages.
- **Leverage Point:** An area where small change can yield large improvements in a system.
- **Reinforcing Process/Loop:** Along with balancing loops, reinforcing loops form the building blocks of dynamic systems. Reinforcing processes compound change in one direction with even more change in that same direction. As such, they generate both growth and collapse. A reinforcing loop in a causal loop diagram depicts a reinforcing process. Also known as vicious cycles or virtuous cycles.
- **Balancing Process/Loop:** Combined with reinforcing loops, balancing processes form the building blocks of dynamic systems. Balancing processes seek equilibrium: They try to bring things to a desired state and keep them there. They also limit and constrain change generated by reinforcing processes. A balancing loop in a causal loop diagram depicts a balancing process.

B Building Reuse System

B.1 Building Deconstruction Management System

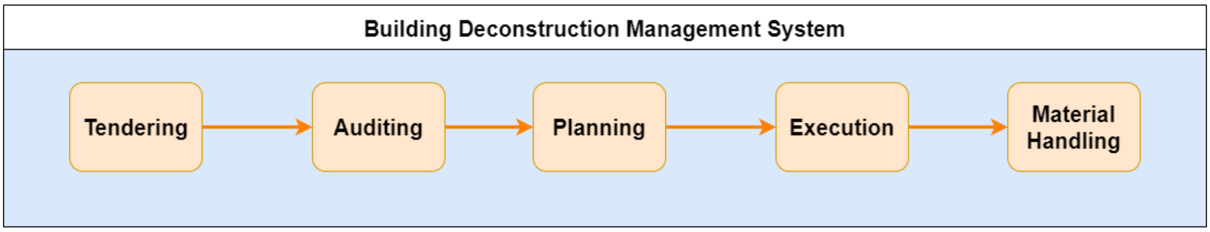

Figure 37: Building Deconstruction Management System (own illustration)

Tendering:
The first process within the system starts with a client tendering out a building identified for deconstruction. Several criteria are defined by the clients with respect to sustainability, reuse/recycle rate, environmental impact, noise, safety etc. in order to evaluate the bidders. The bidders are the demolition contractors who are required to conduct a preliminary study for auditing and develop a deconstruction plan. The demolition contractors are expected to submit a bid based on their preliminary study. These contracts are generally not awarded to the lowest-bidder but are evaluated based on the idea of 'Economically most advantageous tender' (EMAT).These are price-quality tender in which the contract is awarded to the bidder who can satisfy the stated criteria at the best possible rates. These evaluations encourage the contractors to obtain maximum value by retrieving reusable building components.

Auditing:
Auditing the building is mainly concerned with developing the building inventory. It is essential to note that while working with old buildings, the documents are usually not available and the contractors have to adopt manual building survey in such cases. The auditing involves two types of surveys - building survey and structural survey. The building survey involves the assessment of building materials for their quality, quantity, toxicity, etc. and the examination of surrounding site conditions. This is followed by the structural survey in which the structural framework of the building is checked for its quantity and performance. The structural survey is mainly done to ensure the stability of the building during the entire deconstruction process. It is at this stage that the contractors specify which building components are suitable for reuse. The deliverable after this stage is a detailed building inventory with quantity, quality, material and structural performance specifications and the reuse potential of the identified components.

Planning:
The planning stage deals with mainly the identification of demolition technique and is significant in deciding the safe retrieval of reusable components. It involves cost estimation, scheduling, resource allocation, development of risk management and material management plan. The material management plan is developed based on the waste hierarchy framework as shown in figure 5 and the materials suitable for reuse, recycle and disposal are categorised. The cost estimation is also conducted in reference to the building inventory data and the end destination of the materials. It is at this stage where the potential buyers are contacted for the sale of the retrieved components. These potential buyers could be small private firms with offline markets, other established online markets, architects/designers, etc.

Execution:
The execution process often starts with site preparation and removal of hazardous materials. This is followed by the deconstruction of non-structural components also called as 'soft stripping' which comprises the removal of windows, doors, frames, sanitary fittings, floor coverings, etc. These components or materials are separated into different streams based on the material management plan. After the removal of all non-structural elements, the deconstruction of structural framework is started. Finally, the site is cleaned and handed over to the client. Safety of the people and environment takes precedence during execution and a proper record of progress is maintained in a project planner.

Material Handling:
Material handling generally has three options; namely, reuse, recycle and disposal. The building com-

ponents suitable for reuse are separated, cleaned, packed, documented and stored. Based on the plan, these components are transported to the location of the buyers or stored until a potential buyer is found. These could be the location of another new construction project or a storage facility for second hand materials. If the components are required to undergo some processing or refurbishment or up-cycling, these are sent to the processing units. The materials and components which are not suited for reuse, are directed towards recycling and disposal to landfills or incineration.

B.2 Building Design Management System

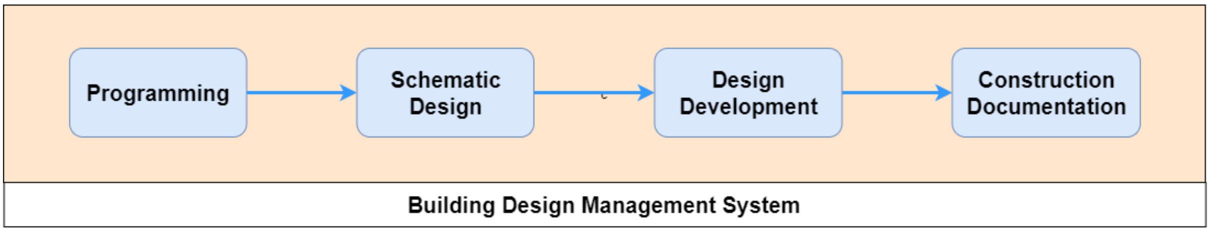

Figure 38: Building Design Management System (own illustration)

Programming:
This phase is also referred to as 'Program of Requirements' and consists of understanding the expectations and requirements of the client. A general layout on the positioning and orientation of spaces is drafted. It also involves preliminary site investigation comprising of applicable zoning, building codes and other regulatory requirements. The client is expected to work closely with the architect for clear communication and understanding of the project scope. This is mainly an information gathering phase and the format of deliverable varies based on the involved stakeholders.

Schematic Design:
The program of requirements from the previous phase is translated into an efficient building design during this stage. As the name suggests, this phase is fairly conceptual in nature. Usually the architect has a prominent role during this stages. However, other experts may also participate depending upon the complexity of the project. The deliverable in this phase is mainly the preliminary drawings such as floor plans, elevations and site plan. The client and the architects work closely with each other during this stage. The schematic design model confirms the requirements of the clients and narrows the scope of project.

Design Development:
This phase is a logical extension to the schematic design phase. The main goal of this phase is to define and develop the important aspects of the project. The role of structural engineers, HVAC installation engineers, building physics engineers, etc takes a prominent role during this phase. The exterior, interior layouts, room sizes, and materials are more fully designed. The engineers will further develop the HVAC, plumbing, and electrical systems. The deliverable in this phase is a even detailed set of drawings as compared to the schematic design phase. In addition, it also specifies the materials that have been selected, installation instructions, quality control requirements, and other technical information. An updated cost estimate is usually produced as well.

Construction Documentation:
This is the phase where intricate details of the project is finalized. The design development drawings and specifications from the previous phase are detailed out to be given as an input to the construction contractor. It generally comprises of building component connections, material specifications. finishes, appliances and equipment to be installed, etc. This phase requires the most time and is very critical to successfully and accurately execute the designs. The deliverable from this phase is a detailed set of drawings and specifications referred to as 'Construction Documents'. These documents are used as input to acquire necessary permits from authorities and bidding quotes for the contractual work.

C Systems Thinking and Modelling - Phase and Steps

Phases	Steps
Problem Structuring	1. Identify problems or issues of concern to management
	2. Collect preliminary information and data
Causal Loop modelling	1. Identify main variables
	2. Prepare behaviour over time graphs (reference mode)
	3. Develop causal loop diagrams (influence diagrams)
	4. Analyze loop behaviour over time
	5. Identify system archetypes
	6. identify key leverage points
	7. Develop intervention strategies
Dynamic modelling	1. Develop a systems map or rich picture
	2. Define variable types and construction stock-flow diagrams
	3. Collect detailed information and data
	4. Develop a simulation model
	5. Simulate steady-state/ stability conditions
	6. Reproduce reference mode behaviour (base case)
	7. Validate the model
	8. Perform sensitivity analysis
	9. Design and analyse policies
	10. Develop and test strategies
Scenario planning and modelling	1. Plan general scope of scenarios
	2. Identify key drivers of change and keynote uncertainties
	3. Construct forced and learning scenarios
	4. Simulate scenarios with the model
	5. Evaluate the robustness of the policies and strategies
Implementation and organizational learning	1. Prepare a report and presentation to management
	2. Communicate results and insights of the proposed intervention to stakeholders
	3. Develop a microworld and learning lab based on the simulation model
	4. Use learning lab to examine mental models and facilitate learning in the organization

Source: Reprinted from " A Methodological Framework for Systems Thinking and Modelling (ST&M) Interventions" ((Cavana & Maani, 2000))

Table 8: Systems Thinking and Modelling Process

D Interview Protocol: Semi-structured

Date	____________________
Name of Interviewee	____________________
Organization	____________________
Designation	____________________

Introduction

- Second-year student of the Masters in Construction Management and Engineering
- Currently doing my Graduation research thesis with Witteven+Bos on understanding how systems thinking approach can be used to develop a digital platform for facilitating the design of new buildings with recoverable building components from existing buildings?
- What is your position within the organization and how long have you been associated with this organization?
- Research Goal

Purpose of the Interview:
Several studies have been conducted for the safe deconstruction of existing building stock in such a way that maximum amount of reusable materials and components are recovered. However, a major drawback observed is that despite a supply of second-hand materials in the market, there is a lack of demand from the client side. It is important that an initiative be taken by the designers to incorporate such materials in their designs. The main purpose of the interview is to understand how the barriers in reuse are perceived within the context of Design process of such building projects.

Questions for the Architect

- Studies have proved that it is technically possible to include used materials and components in new designs. What is the current scenario in the industry with respect to implementing it practically? Have there been such projects, if yes/no, why?
- What are your thoughts if you were asked to design a building with reusable elements? What are the major challenges you expect?
- The design of the building needs to be flexible to incorporate reused elements. Also, the aesthetics? What are the major technical challenges you expect?
- The design process will also need to be changed. Architects and structural engineers need to keep their design flexible. Will that be a problem? If yes, how do you think can it be solved?
- As an architect, which layers of the building do you think can accommodate used elements? (walls, facades, windows, doors, etc)
- What type of building projects do you think would be of more interest? Residential building/commercial building)?
- What will be information you are looking for when you need to include used elements in design?
- What are the quality checks or performance requirements (with respect to the standards) you recommend for reusable elements?
- Projects in the industry such as BAMB and Madaster are initiatives to develop online database of building materials and components. Do you think it will help in the concept of reusing building elements?
- There are very few established online markets dealing with such second-hand materials. Have you explored them? Any thoughts on it?

- Research says there is often a lack of demand for second-hand materials in the market. Should there be an initiative from the designer's side, say an organization like W+B who are design consultants? How?
- Demolition contractors often do not invest in deconstruction and recovery of reusable elements because of demand uncertainties. In such a situation, do you think if instead of focusing on the market, dealing with demolition contractors directly can help?
- Do you think a platform where demolition contractors and designers can interact and share their requirements and availability can help?
- What are type of tools/ software you use for designing? Do you think that is sufficient to work on such projects? What other tools do you expect to make the process easier?
- Currently, designers are focusing on projects which can be deconstructed in future on one hand. On the other hand, there is a need to reuse old materials. How can these to be connected? Is it possible?

Questions for the Structural Engineer

- How are you involved as a structural designer right from the conceptual design stage to final design stage of a project?
- What is the type of information that you receive from the client/architect before starting to design the structural system of the building?
- What is the tool/software used for structural designing?
- What is the format of informational database exchange (BIM model/documents)?
- Which actors do you interact with while designing the project?
- Do you have any prior experience in using reused components in design? If not, why do you think it has not become conventional yet?
- What are your thoughts if you were asked to design the structural system with reused structural elements? How different will it be as compared to the existing design processes?
- What will be the additional information (age, residual strength, quality certification, etc.) that you will need if reused elements are involved?
- Which stages of the design phase will you be needing specific information?
- The structural engineer will have additional responsibilities of performance assurance of the reusable elements before including them in the project. This calls for interaction with the demolition contractor. What type of informational exchange do you think is needed between a structural engineer and a demolition contractor?
- The design of the building needs to be flexible to incorporate reused elements. Do you think that will be a major challenge to face?
- What structural components can be substituted with reused elements in your opinion? (beams, columns, floor slabs, connections, etc)
- What type of reused material do you think is easier to work with in a structural system? (steel, concrete, etc)
- What is the structural composition of commercial buildings in general (steel, concrete, composite)?
- What are the quality checks or performance requirements (with respect to the standards) you recommend for reusable elements?

Questions for the Circularity Expert

- Studies have proved that it is technically possible to include used materials and components in new designs. What is the current scenario in the industry with respect to implementing it practically? Have there been such projects, if yes/no, why?
- Should there be an initiative from the designer's side, say an organization like W+B who are design consultants? How?
- The design process will also need to be changed. Architects and structural engineers need to keep their design flexible. Will that be a problem? If yes, how do you think can it be solved?
- What do you think will be the major challenges to work on a project where we could incorporate used materials in new buildings?
- There are very few established online markets dealing with such second-hand materials. Have you explored them? Any thoughts on it?
- Considering that the market is not established, do you think if instead of focusing on the market, dealing with demolition contractors directly can help?
- Even if demolition contractors carefully deconstruct a building, storage of the material is an issue because of lack of demand. In the absence of a well-established market, do you think working at project-to-project level will help? (Deconstruction project-to-new building project)?
- Do you think a platform where demolition contractors and designers can interact and share their requirements and availability can help?
- Projects in the industry such as BAMB and Madaster are initiatives to develop online database of building materials and components. Do you think it will help in the concept of reusing building elements, especially old buildings?
- Information in old buildings is not available in advance to develop inventories and so establishing a marketplace is difficult. Demolition contractors say most of it is explored only when a building is actually demolished. So, my thoughts say working on project to project level for old buildings is a better solution than just looking for online markets. What are your thoughts?
- Currently, designers are focusing on projects which can be deconstructed in future on one hand. On the other hand, there is a need to reuse old materials. How can these to be connected? Is it possible?

Questions for the Demolition Contractor

- How do you get your projects? Do you bid on projects or you have close cooperation with contractors or clients and you directly do the job?
- Out of these projects, how many them are generally focused on circular demolition process?
- What are the stages involved in a circular demolition process? (as per theory – permits, auditing, deconstruction planning, performance testing)
- In the circular demolition process, is the focus more on recycling or reusing? Are the uncertainties in demand a factor that you don't take more materials for reuses?
- Reuse is mainly wood, plastics and concrete. Any attempts to recover structural elements? Is it at the materials level (eg. Bricks) or at the component level (eg. Steel Beams)?
- Is recovering structural elements for reuse challenging? What are the major technical challenges faced?
- Do you audit the project in order to create an inventory of materials, components? What is the type of information that you capture?
- Demolition contractors say most of it is explored only when a building is actually demolished. Developing an inventory is difficult. What is your opinion?

- How do you do the performance testing of components? Can this information be given before the deconstruction?
- I have seen that you have a separate marketplace established. How is the demand for the reusable materials ?
- How do you do the storage of the materials?
- For reusing elements, do you think putting up a building before the demolition can help in attracting buyers? Do you think if instead of focusing on the market, dealing with design consultants directly can help, working at a project-to-project level?
- At what stage do you want to the architects to get involved? Before the demolition? How can you transfer the information in a building to the architects? Mainly the performance measurements.
- Do you think a platform where demolition contractors and designers can interact and share their requirements and availability can help? Especially the problems with storage and transportation?

E Game Elements

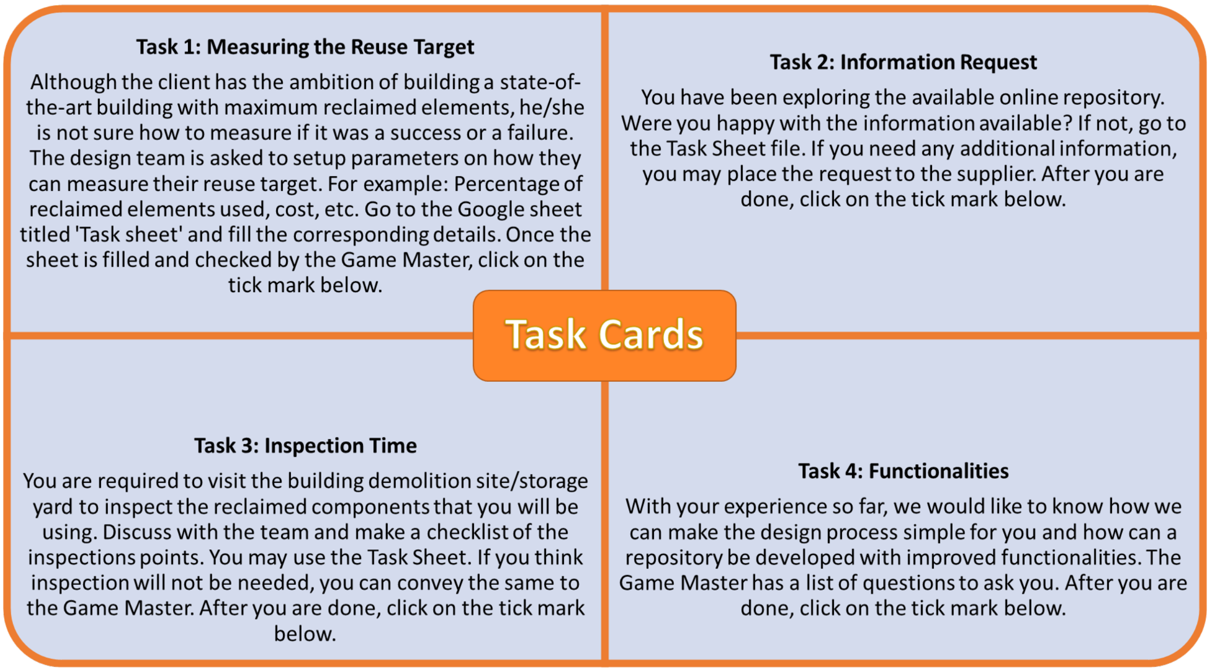

Figure 39: Task Cards

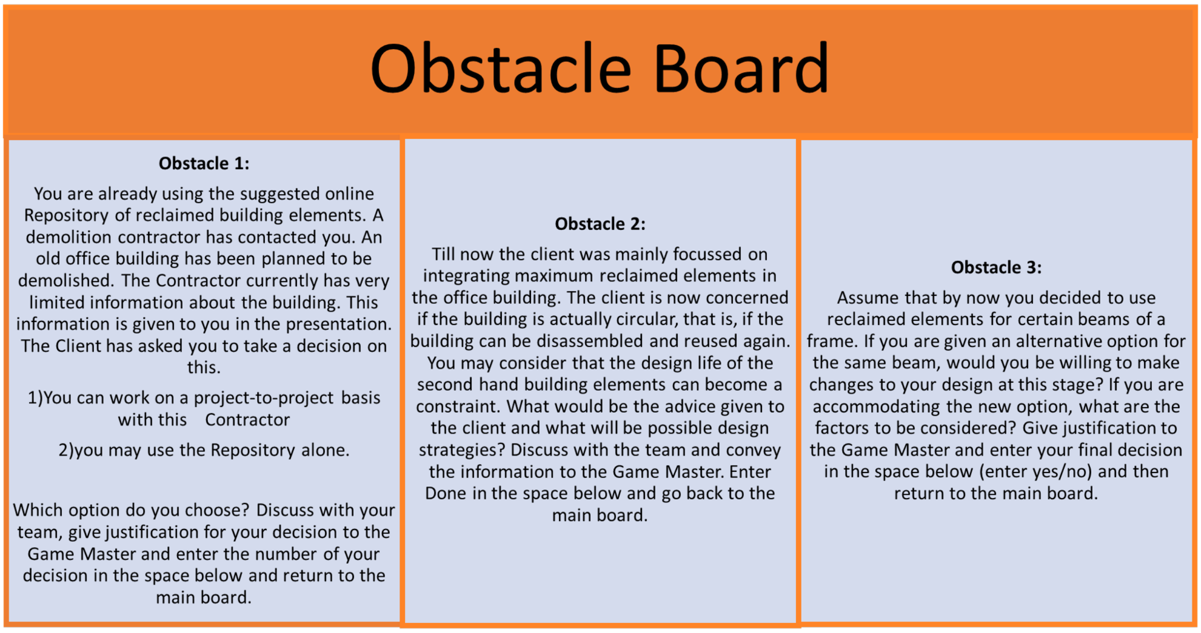

Figure 40: Obstacle board

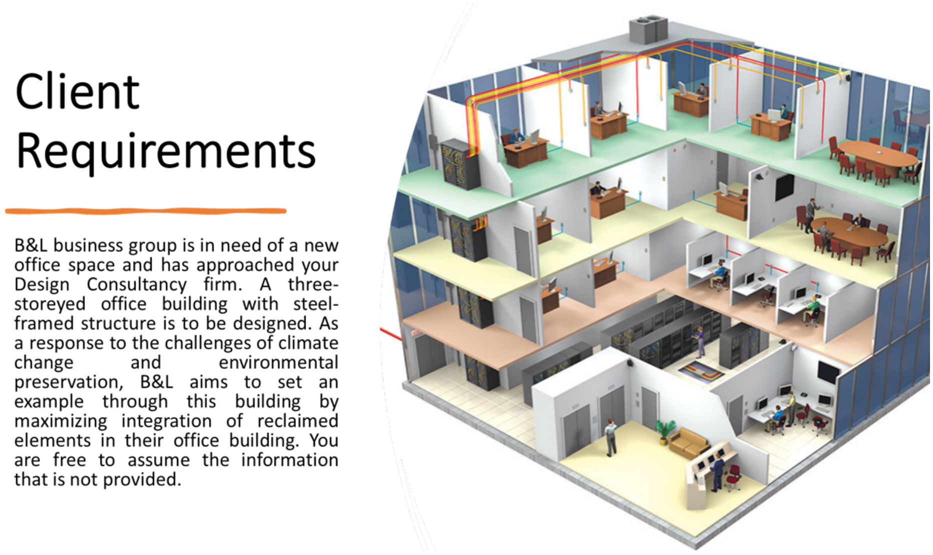

Figure 41: Client Requirements

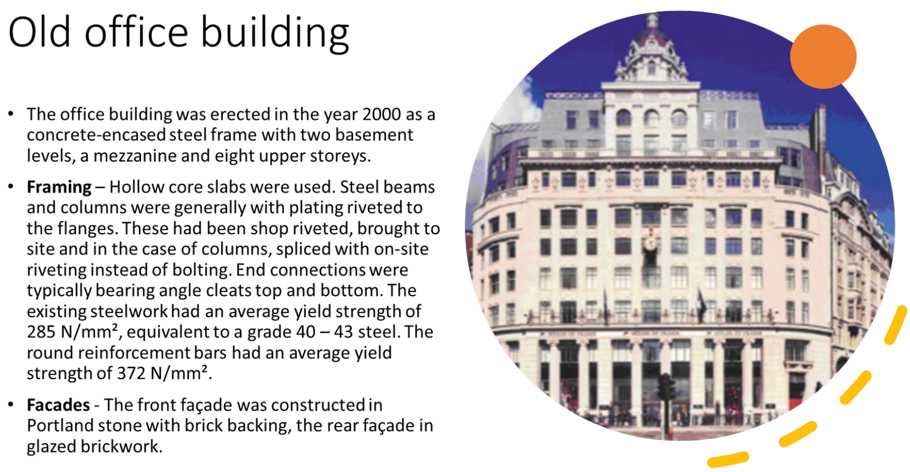

Figure 42: Existing Building Stock

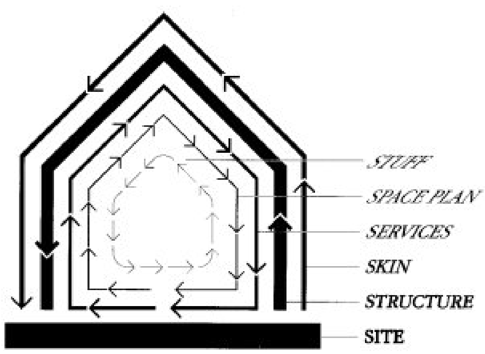

Figure 43: Building Shearing Layers
(Reprinted from "Innovative Built Heritage: Adapt the Past to the Future" ((Pereira Roders et al., 2005))

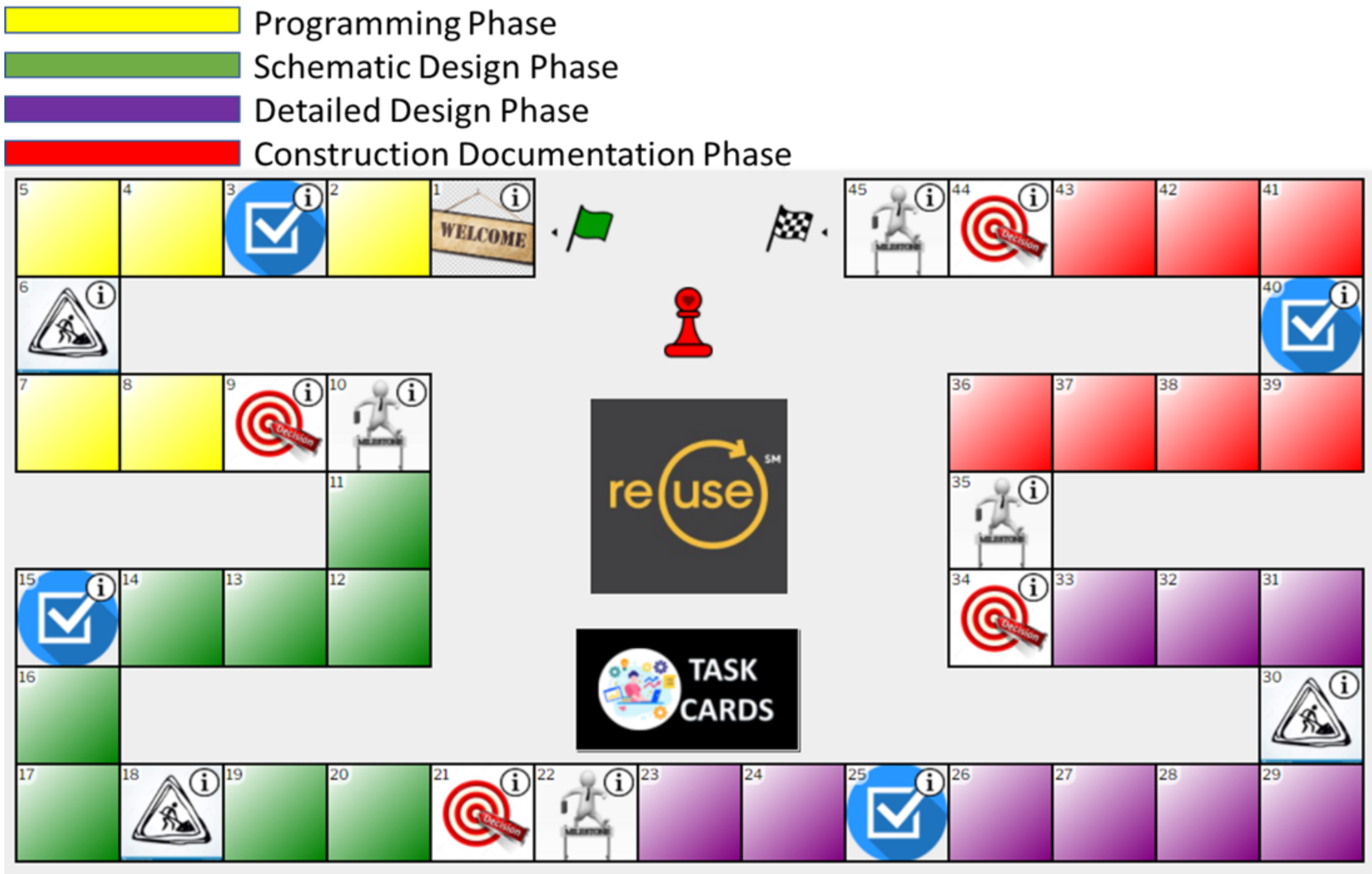

Figure 44: Game Board

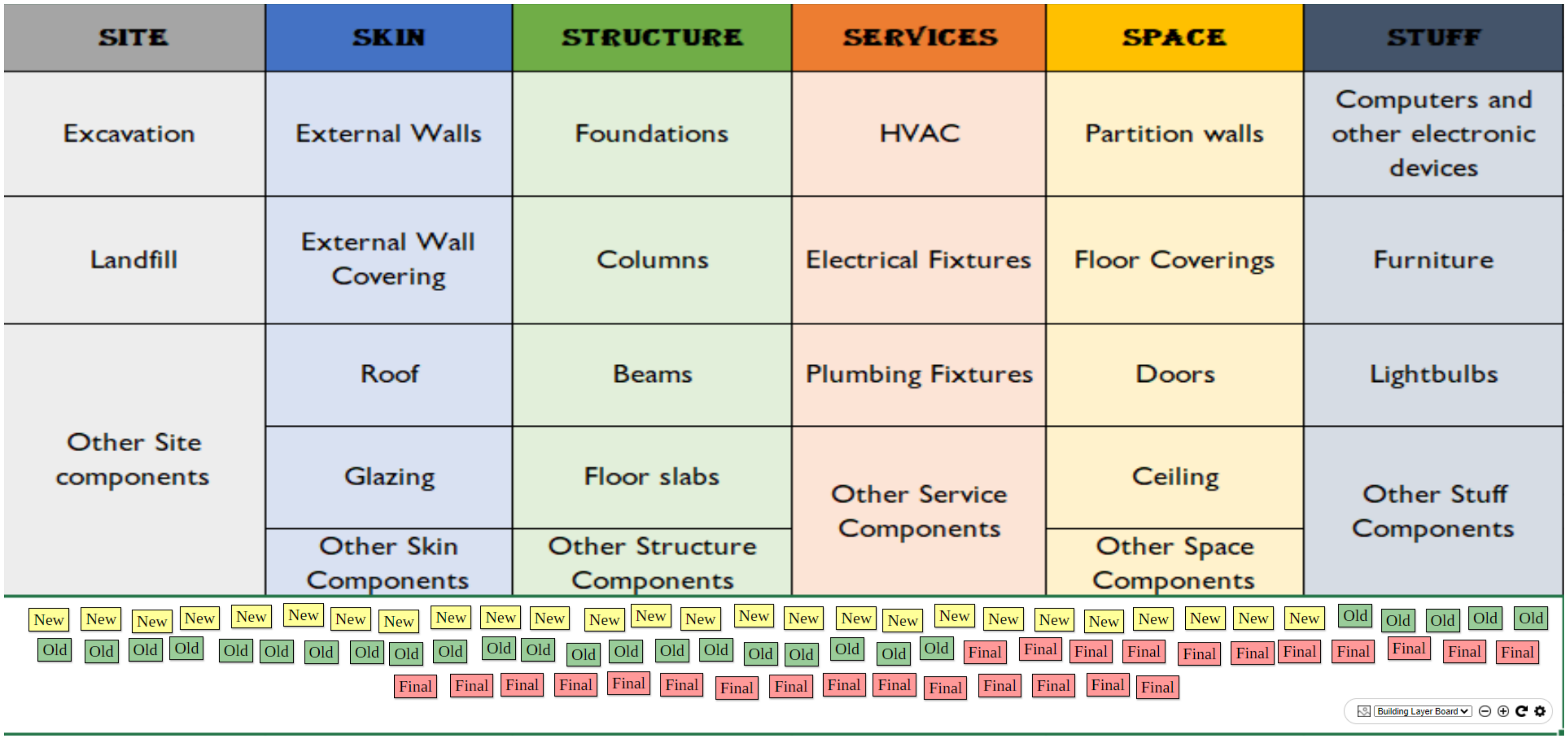

Figure 45: Building Layer Board

F Key Variables List

Key Variables	
Accessibility to Desired products	Localization of market
Accessibility to Information	Maintenance of Information Database
Adequacy of IT infrastructure	Negative Perception
Availability of Desired product	No. of Projects
Awareness	Non-standard products
Building owner/supplier initiatives	Performance & Quality assessment
Centralization of Information	Price of recovered products
Client Initiatives	Processing costs
Collaboration	Product Quality improvement efforts
Communication of Quality requirements	Project cost
Communication of Requirements	Quality feedback
Customization in supply	Quality of products
Data quality Improvement efforts	Recovery rate
Data Volume	Registration of supply products/Existing buildings
Demand	Regulations for Testing and Approval
Design flexibility	Searchability
Design Process efficiency	Shared knowledge
Designer Initiatives	Supplier Network
Efficient Sourcing and Procurement strategies	Supply
Environment and Safety Information	Timely availability
Experience	Transportation costs
Information quality feedback	Usage rate of Recovered elements
Infrastructure and Recovery facilities	

Table 9: Key Variables