Economic Feasibility of Reusing Structural Components

Master Thesis by Ilma Jabeen

TU Delft

"How to quantitatively assess the economic feasibility of reusing structural components from existing buildings into new construction?"

By

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in partial fulfilment of the requirements for the degree of

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PREFACE

This thesis report is the final product toward the completion of my master's degree in Building Engineering. The topic of this thesis is very dear to my heart. I recall flying to The Netherlands from India with a dream of acquiring knowledge on sustainable practices in building construction. My journey at TU Delft has been truly outstanding and overwhelming.
I cannot remember the number of times I had break downs and self-doubt nor can I count the events where I excelled beyond my capabilities. This experience has certainly improved me on a professional as well as personal level.

I would like to extend my heartfelt thanks to the chair of my committee, Dr. H.M. (Henk) Jonkers, for guiding me throughout this journey. His friendly demeanor and critical remarks kept me driven and motivated. I would also like to thank my first supervisor, Dr. D.F.J. Schraven, for enriching my understanding of sustainability and circularity from an economic point of view and my second supervisor, Ir. S. Pasterkamp, for helping me build and improve the research framework. It has been a remarkable experience working with all of them.

I would also like to express my gratitude to all the people who participated in the research. Firstly, I want to thank DGBC for helping me collect data for the case study used in the research. Secondly, I thank all the nine interviewees from the construction industry who invested their time in the research and provided the valuable insights.

I sincerely thank TU Delft for granting me the honor "Justus & Louise van Effen Excellence Scholarship". It has helped me immensely to survive through my studies without any financial limitations. Lastly, I want to dedicate this work to my mother, Farzana Jabeen, who enabled me to follow my dreams. I would like to thank Aksa and Rohit for supporting and loving me though sanity and otherwise. I am grateful to all my friends and peers for being a part of this beautiful journey. Without them, I wouldn't not have been able to pull this through.

Ilma Jabeen,
Delft, August 2020

EXECUTIVE SUMMARY

The construction sector is one of the most important sectors for the economy of a country generating jobs and revenue. However, the operations within the sector are linear in nature which leads to excessive waste generation. Traditionally the buildings are constructed, used and demolished in a destructive way generating huge amounts of mixed mineral rubble. This waste accounts for 25%-30% of the total waste generated in the EU (Commission European, 2019b). Meanwhile, more and more natural resources such as sand, gravel and minerals are extracted to meet the demand for new building construction.

The Netherlands has the vision to be completely circular by 2050 cutting its raw material consumption to half by 2030 (Netherlands Statistics, 2019). However, the construction industry is far from it. To close the building material loop cycles, it is imperative to reuse secondary building materials and introduce them back into the use cycle without extracting more natural resources. However, EOL planning is often forgotten during the design and the use phase of a building. Value recovery is not included in the building life cycle. As a result, the building is demolished in a traditional way without recovering value from the components.

State of the Art Reuse: In The Netherlands, only 3-4% of secondary materials are reused currently as most of the treatment is focused on recycling. 90%-95% of the CDW (Construction Demolition Waste) is recycled which is then consumed by the Dutch Road sector (Michael, 2018). However, this practice of using EOL concrete for road embankment is not sustainable as it is expected to fall to 40% by 2025 as the demand for road development is decreasing whereas the building stock reaching EOL is expected to increase in the coming years (Lotfi et al., 2017).

Reuse although a higher- level treatment method, is rarely adopted. It is limited to the reuse of products such as doors, windows and interior installations. Existing demolition methods do not allow for product recovery as it a costlier and time-consuming process. It requires skilled labour, knowledge and collaboration amongst the stakeholders to deconstruct for reuse. The knowledge of the know-how of recovering structural components is found to be limited.

Furthermore, there is no tool or framework to quantitatively assess the economic feasibility of reusing components well before demolition. The available methods for assessing reuse feasibility are found to have a futuristic approach and cannot assess the economic feasibility quantitatively. Therefore, the Feasibility Calculation Tool is developed in this research which is a practical framework capable of quantitatively assessing the reuse potential of the components. It provides clear guidance to stakeholders on how to assess if the components from existing buildings can be profitably extracted for reuse.

Structural Floor Reuse: Reuse of structural element is very rarely seen in practice, especially for a whole concrete element. Although a building consists mainly of structural components yet the reuse of these components is yet not common as it is more complex and time-consuming to assess the quality of structural components than non- structural components (Bleuel, 2019). The structural layer consists of various components like beams, columns, walls, floors, foundations, etc. The reuse of these components is difficult but would result in high-value recovery. The general perspective of concrete and recycling industry is that concrete has the lowest reuse potential when compared to steel and timber (Hradil et al., 2014). Hence concrete components like floor slabs are seldom recovered for reuse.

Much of the environmental savings can be made by reusing components from old buildings into new buildings. These savings are particularly high for structural floor elements as it saves the embodied energy spent into material extraction, product manufacturing and logistics into delivering the product. Concrete floors present a more viable reuse case than other structural components as these are planar components constituting a large volume of building materials, have greater dimensional flexibility and are more standardized than others.

Deconstruction for Reuse: Unlike demolition which is a simple and quick process to turn down the building and clear the site for the new project, deconstruction is a much more complex process, involving the deconstruction stage, material handling stage and the consumption stage. It begins with obtaining the permit, doing the site audit, making detail inventory of the components, drafting the deconstruction and waste management plan, advertising to find buyers, preparing the site and recovering the components from temporary layers of the building i.e. soft-stripping. Thereafter the actual execution or the disassembly process starts with the performance testing of the components. The level of testing depends on the presence of documents and the requirement of the user. There is no performance protocol, second-party conformity tests are done when the end-user wants to tests for the quality. Then, starts the material handling stage. The first step is to modify the components to fit the requirement of the new use. However, the highest value recovery is with no modification, i.e. using the components as they are. Salvage components are then stored at either the deconstruction site, the new construction site or at a designated storage yard. When stored at the deconstruction site, they can be stored virtually without getting deconstructed until a buyer is found. It saves extra transportation and damage to the elements; however, one needs to pay operational costs. The components are then transported from the deconstruction site to either the end-user, the storage yard or the construction site. From a conceptual point of view, the deconstructed components should be repaired and certified before reuse. However, they are not repaired in practice nor is there any protocol or guideline to certify these components. The secondary products after deconstruction are owned by the contractor, the value of which is subtracted from the contract price.

Various costs are incurred during deconstruction such as the deconstruction, modification, transportation and storage costs. The deconstruction cost is fixed for a given project whereas the modification, storage and transportation costs are the variable cost components. Deconstruction costs is also the highest cost in the reuse process followed by modification, storage and transportation. For an economically feasible reuse case, the net cost of reuse (R_C) is to be less than or equal to the cost EOL treatment in a traditional demolition (C_{EOL}). Tipping points are defined as the highest values of variable cost components beyond which reuse of the given component turns uneconomical. It represents the maximum budget that can be spent on a variable cost while keeping the total reuse cost lesser than EOL cost.

Three different reuse scenarios are developed to analyze the variable costs components of the reuse cost and their interaction with the fixed components. There are three reuse scenarios: Direct On-site reuse (RS1), Direct Off-site reuse (RS2) and Indirect reuse (RS3). The first scenario is RS1 where the recovered products are reused on the same site, i.e, no storage and no transportation cost. The highest cost savings are observed in this case (Glias, 2013). The second scenario is RS2, where the components are deconstructed from one site and taken to another site for reuse. It the second most efficient scenario after RS1 as there is already a demand for the deconstructed components at another site. In the last scenario (RS3), the products are recovered from the building, stored at a facility until a buyer is found and then delivered to the end-user. This is the least desirable scenario but it is most commonly seen in practice.

Various factors are found to affect reuse cost. The results of analytical hierarchy process suggest that "Time Constraint" influences the reuse choices the most. Often the owner wants to get rid of the old building at the earliest to start the new project. However, these strict deadlines set by clients hinder effective deconstruction. The most desirable option is to involve the demolition contractor in the early stages of permit and planning thereby allowing him the time he needs to find a buyer. When there are no time constraints, it gives the contractor bigger opportunities to find buyers for reuse. One can sell the element directly on-site if the time is there, it saves extra transportation and storage cost. Other factor influencing the reuse cost are the type of connection, method of construction. The most desirable connections are "dry+ demountable" connections with the prefabricated components that are designed to be disassembled at EOL. Having the documents in place further reduces the time and effort that goes into the investigation, the risk of accidents and unplanned collapse. Other factors such as site accessibility, quantity and age have relatively lower influence over the reuse cost.

Feasibility Calculation Tool: The tool is developed to determine if it is feasible to reuse a given component or not. It can be particularly useful for clients and owners such as a municipality, state authorities, real-estate developer or individuals who face the dilemma of reusing or demolishing. It is a predictive model which attempts to predict the future costs taking into account the variables which influence the costs. It is intended to give quantitative tipping points in terms of modification, storage and transportation type, under which reuse becomes economic.

It is developed using Microsoft EXCEL program. Since the deconstruction cost is a fixed cost whereas the modification, transportation and storage are variable in nature, to achieve a feasible reuse case, different combinations of variable costs are generated using the concept of random sampling. The tool calculates the feasible reuse cases and for these cases, it generates quantitative tipping points for the variable costs. Tipping point is the highest value of variable cost for which reuse is still economic and beyond which reuse turns uneconomic.

An interactive user interface is developed which allows the users to try and make different reuse choices and see for themselves if these are economic or not. The users can choose themselves different values of transportation, type of modification and storage and get an instant decision if the combination opted by them is economically feasible or not. It shows the reuse cost expressed in euros, i.e. for the selected type of modification, transportation and storage, how much will it cost to reuse it. The deconstruction fixed cost is automatically taken into account by the tool. The results then show the decision as to if this combination results in an economically feasible reuse case or not. It also displays, under which reuse scenario is the selection made by the user-defined, is it a scenario 1 (RS1), scenario 2 (RS2) or scenario 3 (RS3) case.

The tool has been tested on a case study and is found to have no conceptual or technical errors. Furthermore, the results generated by the tool have been verified with the known facts. The validation results for the tool are also positive. It can correctly generate the effect of environmental impact cost and varying salvage on the resultant reuse cost and tipping points. The sensitivity analysis shows that FCT is sensitive to the changing inputs such as factors affecting the reuse cost.

The results of FCT show that it is most feasible and economic to reuse components directly on the same site (RS1) then to transport them to another site for reuse (RS2). However, for the existing building stock, it is more probable to reuse under RS3 than RS2 and RS1 as the existing stock is not designed to be reused. Instead, a buyer should be found who has no or minimum modification requirements i,e, RS3 case. Furthermore, taking the environmental impact of reusing secondary components into account improves the reuse feasibility. The reuse cases which are otherwise not economically feasible turn feasible once the environmental impact costs are considered, in other words, once the polluter is made to pay the price. Furthermore, planning for the EOL of the building should be done well in advance to allow for sufficient time and efficient recovery. The owner should be motivated for deconstructing circularly, allow sufficient time and if he fails to reuse materials himself, he should allow for collection and sale of secondary products by the demolition companies to a third party. The demolition contractors, on the other hand, are found to depend on the question from the owner to reuse. However, they must make voluntary calls for deconstruction.

Furthermore, taking the environmental impact of reusing secondary components into account improves the reuse feasibility and the tipping points for reuse case. The reuse cases which are otherwise not economically feasible turn feasible once the environmental impact costs are considered, in other words, once the polluter is made to pay the price. The results obtained from FCT also show the effect the salvage value has on the reuse cost. Higher the salvage, lower is the reuse cost. If components are deconstructed with high quality and sold for higher salvage, the tipping points for transportation, modification and storage get improved i.e. they can be transported for higher distances, stored for a longer time and modified to the requirements of end-user.

A combination of policy instruments needed. For instance, environmental policies like the landfill ban, Provincial Environmental Ordinances and Building Material Decree are found to have a positive impact in reuse adoption (Dijk et al., 2000). Tests on increasing virgin materials taxes and/or gravel taxes across Europe suggests that it is profitable to promote reuse(Commission European, 2016). To ensure effective reuse, secondary materials should be made available at competitive prices. It can be achieved by differentiating landfill taxes such that higher taxes are set for reusable products. Having identified the products which need policy support, these taxes can be regulated. Technical and financial support such as tax deduction for salvaged materials, loans for land acquisition to secondary product businesses has a significant role in the creation of secondary markets, employment opportunities and training of labour (Bradley, 2001).

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List of Abbreviations

EOL	End-of-life
CO_2	Carbon dioxide
CDW	Construction Demolition Waste
DFD	Design for Disassembly
HCS	Hollow Core Slab
FCT	Feasibility Calculation Tool
CE	Circular Economy
GHG	Green House Gases
LCA	Life Cycle Analysis
BMB	Block Modular Building
GFA	Gross Floor Area
MCDM	Multi-Criteria Decision Making
AHP	Analytical Hierarchy Process
C.R	Consistency Ratio
RS1	Reuse Scenario 1
RS2	Reuse Scenario 2
RS3	Reuse Scenario 3
GIS	Geographic Information System

1

PROBLEM EXPLORATION

This chapter explores the problem and identifies the need for research and prevailing research gaps. First the problem context is introduced highlighting the role of construction sector including consumption, waste generation and treatment methods. Thereafter, the need for research is identified based on the review of the available literature on the state of the art of component reuse in the industry and the methods to assess the reuse feasibility. Lastly, the research gaps are detailed out which should be filled in this study.

1.1. Context

The construction sector is one of the most important sectors for the economy of a country. In the EU, it contributes to 9% GDP creating about 18 million direct jobs (Commission European, n.d.). In addition to being a major employer and revenue generator, the building industry is also a large consumer of natural resources. Around 65% of total aggregates (sand, gravel and crushed rock) and 20% of total metals are used by the sector alone with an embodied energy of 20% of the total industrial sector (Herczeg et al., 2014). It also generates the heaviest and most voluminous waste. Traditionally the buildings are demolished in a destructive way generating huge amounts of mixed mineral rubble some of which is recycled and rest is sent for disposal (Michael, 2018). CDW accounts for 25%-30% of the total waste generated in the EU (Commission European, 2019b). Nearly 1/4th of all the output of the sector in the Netherlands is waste (Netherlands Statistics, 2019). It was the highest waste generated by volume in 2016 (Netherlands Statistics, 2019). Meanwhile, the demand for new buildings is on the rise simultaneously. As per RVO.nl, one million new houses are needed until 2040 in The Netherlands (RVO.nl, n.d.). Hence, the existing buildings are getting demolished while extracting more materials for meeting the future demands.

1.2. Need for Research

The need for the research was identified from the review of the available literature on the state of the art of component reuse in the industry and the methods to assess the reuse feasibility. The sources included published works from scientific repositories such as TU Delft repository, Research gate, Academia, etc, using online search engines like google.com.

The Netherlands has the vision to be completely circular by 2050 cutting its raw material consumption to half by 2030 (Netherlands Statistics, 2019). To be circular, resources need to be used consciously keeping in mind their finite nature and be treated most responsibly after use. There are various initiatives and pilot projects to achieve this target. However, the construction industry is far from it since it operates on the linear economic model of produce-consume-dispose. The buildings are constructed using natural resources, utilized during the use-phase and then demolished at the end-of-life (EOL). 90%-95% of the CDW is recycled which is then consumed by the Dutch Road sector (Michael, 2018). However, this practice of using EOL concrete for road embankment is not sustainable as it is expected to fall by 60% by 2025 as the demand for road development is decreasing whereas the building stock reaching EOL is expected to increase in the coming years (Lotfi et al., 2017). To close the building material loop cycles, it is imperative to reuse secondary building materials and introduce them back into the use cycle without extracting more natural resources. However, reuse is still not a preferred activity in the building industry as the cost is often higher than using new materials. In The Netherlands, only 3-4% of secondary materials are reused currently as most of the treatment is focused on recycling.

The concept of deconstruction for component reuse is not new. Despite pilots happening for over 20 years globally to study the feasibly of product reuse, the knowledge and practice of deconstruction are quite limited. The current studies which aim for resource efficiency and closing the material cycle are mostly focusing on recycling the CDW waste instead of strategizing a plan of action for reuse (Coelho & De brito, 2013). The lack of reuse as a building practice is not only due to the difficulty of dissembling the building but also because there is no guiding framework which systematically assesses the reuse potential of components (Durmisevic et al., 2017).

To be adopted in practice, the economic cost of reuse must be cheaper than traditional demolition. However, value recovery after EOL is not a common practice in the building industry. As a result, there is no planning tool to plan for recovering EOL products from the building at highest value. Demolition planning is often forgotten during the design and the use phase of a building. When buildings are not constructed for deconstruction, it has to be very well planned to analyze the various options and determine the cost of recovering components for reuse. However, there is no tool or framework to quantitatively assess the economic feasibility of reusing components. As a result, reuse is limited only to the aggregates separated from concrete because the technology is well established and inexpensive with a developed market for secondary aggregates. There is no reuse on the component/element level as the recovery of secondary components consumes more time than traditional demolition, requires careful dismantling with skilled labour, involves higher risks and has narrow profit margins. The lack of established markets and business networks for secondary materials results in large transportation and storage costs making reuse economically more unattractive. Amidst these challenges, the owner or the contractors are not able to assess the economic feasibility well in advance. It is a risky unknown process for them. Hence the need was identified to develop a tool to quantitatively assess if reuse of components from an existing building is feasible in the future or not.

1.3. The Research Gaps

The available methods and concepts developed for assessing reuse feasibility are found to have a futuristic approach, i.e. not solving the problem at hand but preparing for the future failing to assess the economic feasibility of reuse quantitatively. It is discussed in detail in the following section:

- **Futuristic Approach:** The available reuse tools and frameworks have futuristic approach i.e. they focus on how to build in the future for reuse and not on how to reuse the existing stock. It is believed that effective reuse of components is possible only when it is designed for reuse. There is a growing trend of Design for Disassembly (DFD), in which a structure is designed in such a way that it can be taken apart after EOL for reuse or high-value recycling (Bradley, 2001). However, it does not solve the existing issue of increasing obsolete stock and its demolition. For instance, the work of Ankur Gupta proposes circular procurement while designing i.e. the performance requirements are laid out for buildings to be built such that it is possible to reuse them after EOL. However, it does not suggest the handling of existing stock which is destined to be demolished. Another issue with the existing approach to assess the reuse feasibility is the comparative scale used. It means that the reuse potential of a component is not calculated based on its individual properties. For example, Dominique Bleuel has developed a decision support model for analyzing the reuse potential of HCS (Hollow Core Slab). The model calculates reuse potential based on the comparison between the existing components and the demands of the new structures to be built (Bleuel, 2019).

Hence, the reuse potential can be determined only when the demand is defined. It implies that if there is no building to be built with the secondary component, the reuse potential for the given component cannot be calculated.

- **Not considering cost aspects**: There is a lack of reuse frameworks which take into account the economic aspects of reuse. Most of the academic frameworks available in the literature are centred around the technical feasibility of retrieving the materials. For instance, the framework developed by Elma Durmisevic (Durmisevic et al., 2017) assesses reuse potential in terms of independence of modules and exchangeability both of which are technical parameters used to indicate the level of disassembly. Another tool which focuses only on the technical side is the Reversible Building Design Tool developed in the BAMB project which is developed to facilitate future circular procurements(Durmisevic, 2020). The key indicators for the tool are reversibility of space, structure and materials. The output of the tool gives three scenarios (irreversible, partly-reversible and reversible) based on the properties of the space, structure and material but fails to take into account the cost of reuse in terms of deconstruction, material handling costs and other processes. Other authors who have considered costs elements in their work have not taken the effect of process costs into account. For instance, the research of Amol Tatiya investigates the effect of different design approaches on the deconstruction cost. It resulted in a cost prediction model for deconstruction, however, the tool does not take the process costs such as storage, transportation, modification, etc, into account.

Hence, there is a need to develop a practical tool which quantitatively assesses the reuse potential of the components locked in the existing building stock. The framework should be transparent and provide clear guidance to stakeholders on how to assess if the components from existing buildings can be profitably extracted for reuse. It should also allow one to assess the reuse possibility independent of the demand, on an absolute, not a comparative scale. It can then generate the supply of secondary components for reuse which are to be matched with the demand. It should also consider the execution as well as material handling process and their effect on the overall process.

2

RESEARCH APPROACH

This chapter explains the aim of the research followed by the main research question that the study needs to answer. To answer the main research questions systematically, various sub-questions are formulated. Thereafter, the different stages of the research are elaborated under the methodology section. The methods adopted are also clarified in the methodology section. After methodology, the research outline is explained which contains a description of various chapters the report contains and their relevance concerning the sub-questions they answer. Lastly, the scope of the research is made explicit. The type of component, typology, contextual scope and geographical scope are defined in this section.

2.1. Research Aim

As concluded in section 1.2., there is a need to enhance the knowledge on the subject of component reuse and develop practical systems to assess the economic feasibility of reuse.
This research aims to investigate the conditions quantitatively under which reuse of building components turns economically feasible. The problem to be tackled here is to enable the stakeholders with the knowledge and working tool to assess the reuse feasibility economically well before the demolition of a building. Hence the aim of the research is as follows:

“To develop an economic feasibility assessment tool which gives the quantitative cost of reusing components and process-based tipping points beyond which reuse ceases to be economic.”

The tool is developed to help the building owners and demolition contractors to decide if and when it is profitable to deconstruct the building for reuse. This decision can be made well before demolishing the building.

2.2. Main Research Question

To achieve the aim stated in the previous section, research questions are formed. The main research question to be answered in this report is as follows:

“How to quantitatively assess the economic feasibility of reusing structural components from existing buildings into new construction?”

2.3. Research sub-questions

The research is conducted in three stages: the background study; the conceptual framework and the feasibility calculation stage. To answer the main research question systematically, following sub-questions are formulated within each stage of the research:

<u>Background Study</u>
Q1. What is the state- of- art concerning structural component reuse?

Q2. Why is reuse uneconomic? What are the underlying challenges of structural component reuse?
Q3. What is the process to deconstruct a building for reusing components? How does it vary from traditional demolition practice?

Conceptual Framework
Q4. What are the costs involved in the reuse of structural floor elements?
Q5. What is the feasibility condition? What are the tipping points for an economically feasible reuse case?
Q6. What are the reuse scenarios?
Q7. Which factors influence the reuse cost and how?
Q8. How to make reuse profitable?

Feasibility Calculation
Q9. What is feasibility calculation tool? How does it quantify reuse feasibility?
Q10. Does the tool give realistic results?

2.4. Research Methodology

To answer the research question systematically, a stepped approach is adopted. The research is conducted in three stages, namely:

1. Background Study
2. Conceptual Framework
3. Feasibility Calculation

Stage 1_ Background Study: The background study started with a review of the available literature on the state of the art of component reuse in the industry and the methods to assess the reuse feasibility. The sources included published works from scientific repositories such as TU Delft repository, Research gate, Academia, etc, along with online research using google search. It helped to understand the current trends and practices of reusing building materials and identifying the existing research gap and narrowing down the scope of the research. Since the practice of deconstruction for structural component reuse is relatively new, there is not much published on the details and challenges of execution. Therefore, to fill these knowledge gaps, interactive methods are adopted along with the literature review. The insights are gained from practice by conducting interviews and floating questionnaire to experts as explained below.

- **Interviews**: Interviews were conducted with demolition contractors who are involved in deconstruction and have practical experience of the difficulties and practicalities of on-site deconstruction. The selection of the personnel was based on the demonstrated interest of the company in circular demolition and deconstruction activities. To begin with, the list of demolition contractors was sorted from the VERAS website. VERAS is the industry association for demolition contractors with over 100 demolition contractors as its members (VERAS, n.d.). Furthermore, demolition contractors who have participated in associations for reuse like "insert" were contacted. Insert is an online platform where secondary components are posted by the participating companies to find a reuse for them (Insert, n.d.). Other contractors who were not a part of insert but had their secondary material stores and projects which have been circularly deconstructed were contacted as well.

A semi-structured interview was conducted with each of the interviewees. The first part of the interview had practical questions focusing on the traditional demolition, circular demolition and the deconstruction process whereas, in the second part, the interviewees were asked to filled the comparison matrix (explained later). The insights learned from these interviews helped to develop the theoretical framework as a whole and are referred throughout the body of this report as **"insights from interviews"**. A total of 9 such interviewees were conducted. For privacy reasons, the identity of interviewees is kept discreet in this report and they are referenced as interview 01, 02 and so on. However, the original transcripts of the interviews are made available in **Appendix 1**.

- **Questionnaire:** In addition to the interviews, a questionnaire was made to collect information on the topic of performance testing and certification of structural components deconstructed for reuse. A set of 15 questions were drafted to assess the existing methods, costs and factors which affect performance testing and certification of secondary components. The questionnaire was divided into two parts: the first part focused on the performance testing of secondary concrete floor slabs and the second part was based on the certification of secondary concrete floor slabs. The questionnaire was then circulated to various concrete testing and certification companies. However, the author succeeded in getting two responses from experts. The filled questionnaires are made available in **Appendix 2**.

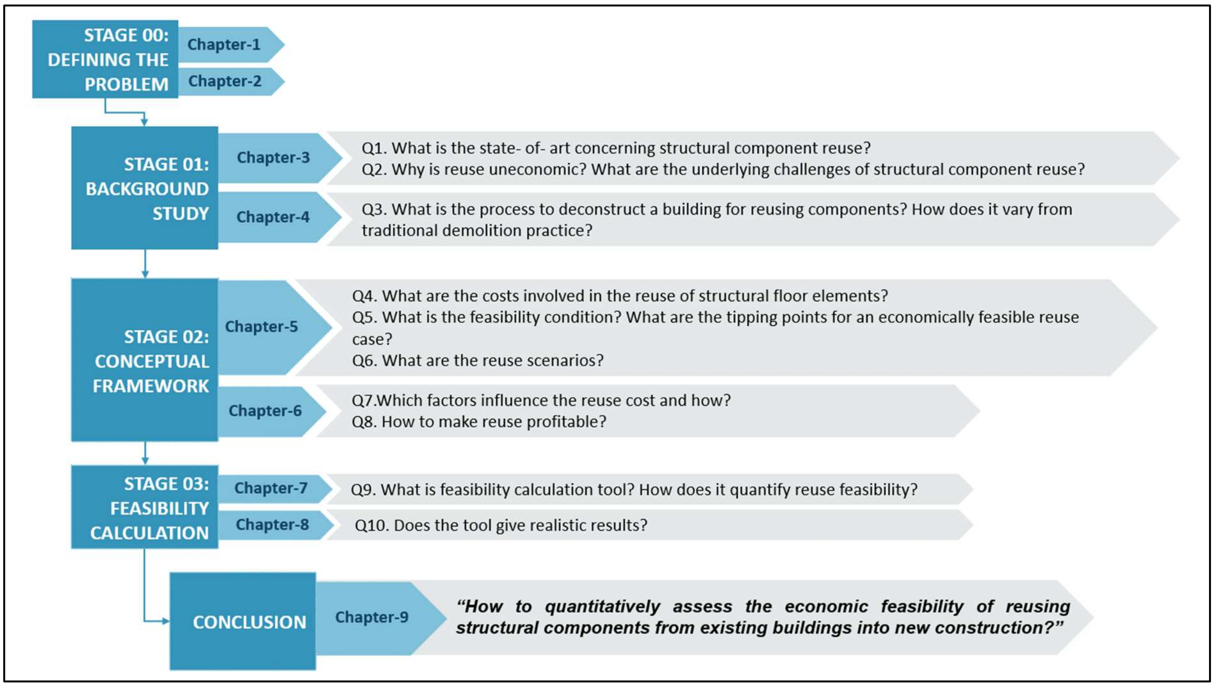
Stage 2_Conceptual Framework:
Based on the findings of the background study, a conceptual cost framework is developed in this stage. To identify the different cost elements involved in the reuse process, a process-driven analysis is done where cost elements are identified as and when they occur in a process. The conceptual framework is also verified with the industry experts during interviews to generate the most practical cost equation. The unit cost of each operation is derived with the help of existing literature. Thereafter, the cost elements are analyzed in greater detail following which feasibility condition is defined along with the tipping points. Thereafter, different reuse scenarios are explained followed by the factors which affect the reuse costs are identified and their effect is determined. The framework concludes with the discussion on how to make reuse a profitable business case.

Stage 3_ Feasibility Calculation:
Based on the conceptual cost framework, the Feasibility Calculation Tool (FCT) is developed in this final stage of the research. First, the development of the Feasibility Calculation Tool (FCT) in Microsoft Excel is explained. The functioning of the tool and the conceptual fundamentals are explained in detail. To ensure that the FCT works as designed and generates reliable tipping points, various evaluations are conducted on the tool including testing on a case, result verification, error calculation, sensitivity analysis and validation based on known facts. The final section of the research, analyzes the results to arrive at conclusions and provide recommendations for various actors and future research. Hence answering the main research question.

2.4.1. Research Outline

The research outline is presented in table 1. Each of the chapters is drafted such that it answers one of the research sub-questions. Chapter 1 and 2 are the exceptions as they do not answer a research question instead explore the main question. Chapter 1 is the problem exploration chapter where the context of the research is introduced, the need for the research is identified with the help of existing research gaps. Thereafter in chapter 2, the research approach is discussed as detailed at the start of this chapter. In chapter 3, begins the introduction to the traditional demolition process and the state of art component reuse. This chapter answers the research sub-question 1 and 2. Next is chapter 4 which elaborates on the process of deconstruction, thus answering sub-question 3. Thereafter chapter 5 elaborates on the reuse costs, feasibility condition and the concept of tipping points, thus answering sub-question 4,5 and 6. Chapter 6 is drafted to answer sub-question 7. Chapter 7 explains the reuse scenarios which answers sub-question 8. Thereafter chapter 8 and 9 explain the FCT and evaluate its function, thus answering sub-questions 9 and 10 respectively. Chapter 10 presents the conclusions of the study and the recommendations for various stakeholders and emphasizes on the direction of future research.

Table 1: Research Outline



2.5. Scope of the research

The scope of the research is **to determine the economic feasibility of reusing concrete floor slabs in office buildings in The Netherlands.**

- **Component: Concrete Structural Floors**

The research focuses on the reuse of concrete structural floors because it results in maximum value recovery in terms of embodied energy and embodied carbon. Floors, in particular, are selected as they are planar components which contain a high amount of concrete, have lesser degradation and provide greater flexibility for reuse. The geometry of floors allows for greater adaptability. Unlike floor slabs, stairwells, lifts shafts and roof components are often difficult to reuse (Glias, 2013). The material scope is set to concrete as it is a common building material and has a technical life of about 200 years (Glias, 2013). The outflow of the building stock reaching EOL in The Netherlands is expected to dissipate high concrete waste products (Icibaci, 2019). It also constitutes a majority of CDW composition. Hence, concrete elements are chosen for investigation in this research.

- **Typology: Office Buildings**

The scope of this research is limited to office buildings. Offices are generally rented for a period of 10 years which can be extended to a maximum of 30 years. However, most of the offices built after the 1980s have prefab concrete elements which have a life of at least 200 years and are used for 25 years on an average (Naber, 2012). Hence office buildings have sufficient remaining service life for reuse. Reusing components from office buildings provides greater flexibility in terms of load-bearing capacity. As per NEN 6702:2007, the live load for office buildings is 2-4 kN/m^2 whereas that for residential Buildings is 1.75 kN/m^2. Based on the loading requirements, the components recovered from office buildings can be used in other offices as well as residential buildings. Another reason to investigate this typology is the method of construction which uses comparatively more standard and repetitive elements than residential buildings allowing for flexible reuse.

- **Contextual Scope**: **Economic Feasibility**

There are various factors which influence the feasibility of reuse such as economic, technical, environmental, institutional, social behaviour, etc. The economic factors emphasize on the costs associated with reuse whereas the technical aspects deal with the assessment of the strength and durability of the secondary component; institutional aspects refer to the policies and the state apparatus in the region whereas the social behaviour represents the cultural outlook of the customers towards using a secondary product. As reflected in the main research question, this research focuses only on the "economic feasibility" of reuse. The decision to focus on economic feasibility was made based on the insights of the interviews where the contractors pointed out economic feasibility to be the greatest challenge for reuse. There was a common consensus amongst all the interviewees that it is technically possible to deconstruct for reuse, however, they do it only when it is economically profitable. Therefore, the focus was set on determining economic feasibility.

- **Geographical Scope: The Netherlands**

The feasibility of building deconstruction varies with the region, country and continent (Bradley, 2001). Different areas use different building methods and materials for construction and have varying prices for labour and machinery. It is therefore important to define the geographical boundaries. This research focuses on The Netherlands and therefore the fixed costs elements and unit prices are derived from the Dutch market. The case-studies used are also within The Netherlands and so are the different stakeholders who were interviewed during this study for inputs and insights.

3

INTRODUCTION

This chapter introduces the concept of reuse, types of reuse and the state of art reuse. It then explains why reuse of structural components is beneficial and should be adopted in practice. Furthermore, it elaborates on the various reasons and challenges which make reuse economically unattractive option. This chapter answers the following research sub-questions:

Q1. What is the state- of- art concerning structural component reuse?
Q2. Why is reuse uneconomic? What are the underlying challenges of structural component reuse?

3.1. Concept of Reuse

Reuse is defined as any operation by which products or components that are not waste are used again for the same purpose for which they were conceived (Commission European, 2016). The concept of component reuse has gained greater importance from the Circular Economy (CE) ideology. CE refers to the system of restoring the capacity of natural resources by reusing products and raw material. CE directs efforts towards minimizing value destruction in the overall system and value creation at each level of process (Bastein et al., 2013).

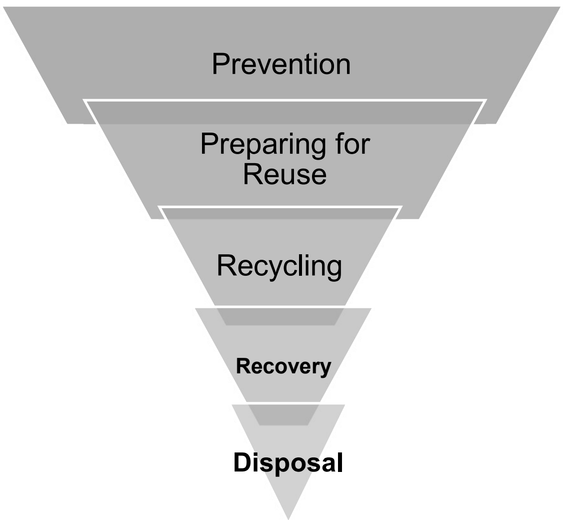


Figure 1: Waste Management Hierarchy (Commission European, 2008)

Reuse is a preferred treatment strategy than recycling (Dijk et al., 2000), (Philip, 2001),(Gilli & James, 2001),(Commission European, 2008). The policy initiatives at the EU level and in The Netherlands explicitly indicate reuse to be a higher priority treatment than recycling. It is further corroborated by the Waste Framework Directive (Figure 1). The hierarchy is developed to ensure maximum resource efficiency where prevention of waste generation is the best practice followed by reuse of waste, recycling, recovery (for backfilling) and last is the disposal of waste. The target for high-level resource efficiency directs all the EU member states to have a minimum of 70% CDW reused, recycled or recovered by 2020(Commission European, 2008). On the national level, it was formulated with similar policies. For instance, the Dutch government in 1980 published the Ladder of Lansink which gave the top-down treatment order as prevention, element reuse, material reuse, useful application, incineration with energy recovery, incineration and landfill. It was then evolved into what is called the “Delft Ladder” which further added flexibility in it by incorporating “construction reuse” as well (Dijk et al., 2000).

There are various environmental, economic and social benefits of reuse. Reuse results in higher value recovery and requires lesser energy than recycling (Tatiya, 2016). Reuse reduces the extraction of raw materials, greenhouse gas emission, energy consumed in production and recycling, etc. Reuse can influence 42% of final energy consumption, 35% of total GHG emissions and 50% of the extracted materials (Herczeg et al., 2014). There is a reduction of about 35% CO_2 when a building is reused and 50% CO_2 for second-time reuse (Naber, 2012). Deconstruction also causes less dust production as a lesser amount of concrete surface is broken thereby producing lesser quantities of quartz in the air. It causes less harm to the workers as well as people in the surrounding area (Naber, 2012).

The economic benefits of reuse are the savings on purchasing new products which are often costlier than secondary products and lower disposal costs as one can save on the cost of recycling and landfilling taxes by diverting the EOL waste into reuse. Lastly, in a scenario where the polluter pays the price of pollution, reuse also saves the environmental costs. Furthermore, reusing building components have social benefits such as job creation in the second-hand market and developing the local network of businesses absorbing large pool of labour (Commission European, 2019a),(Bradley, 2001). Deconstruction being a labour-intensive job can employ at times of crisis. For instance, when a hurricane hit the US, the aid agency MC provided training and job to people by employing them for the deconstruction of the damaged property (Tatiya, 2016).

Types of Reuse: Based on the size of the secondary component, reuse can be of different scales: building reuse, component reuse and material reuse as depicted in figure 2. For instance, reusing crushed concrete in road subbase is an example of material reuse whereas the reusing concrete floor element is a product level reuse.

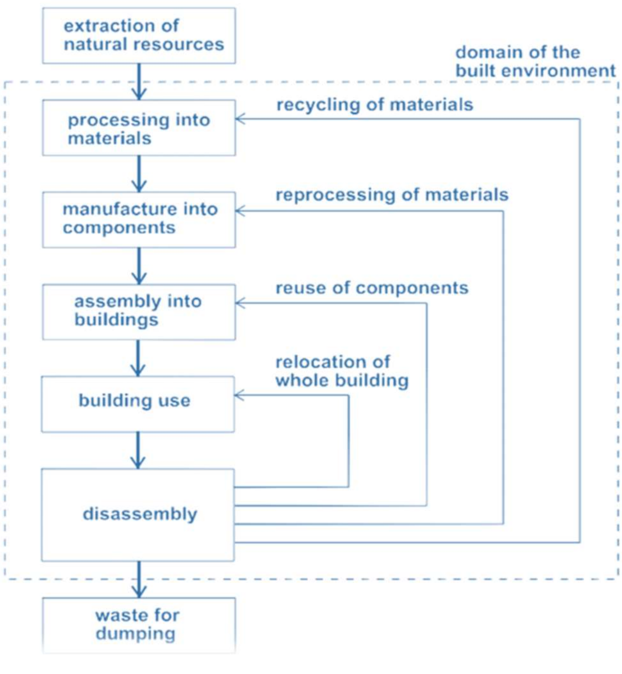


Figure 2: Possible EOL Scenarios for Built Environment by (Philip, 2001).

- **Building Reuse:** In other words, it is the

disassembly of a complete building from one site and assembling it on another site. The maximum value is preserved in case of building reuse followed by-product reuse and least by material reuse in terms of quantitative and qualitative waste prevention (Dorsthorst & Kowalczyk, 2005). It also has the highest environmental savings as larger the secondary product, higher is the environmental benefits (Icibaci, 2019). An example of building reuse is the SUPERLOCAL project (figure 3) which is an area development project with on-site reuse. Structural concrete skeletons are recovered from 2 vacant high-rise apartments for constructing 130 new houses in the area (Superlocal, n.d.). The project is an initiative of the municipality and housing association HEEMwonen.

However, building reuse is difficult to realize and is mostly possible only in case of temporary constructions which are built for short period and designed for deconstruction such that they can be easily assembled, disassembled and re-assembled. However, it does not apply to the existing buildings which are not built with disassembly and reuse in mind. The existing buildings fail to adapt to changing user requirements. A good example of changing user requirements leading to building obsolescence is the office vacancy: the Amsterdam office market now has a vacancy rate of 4.4%, Utrecht 7.6% and The Hague 8.5% (CBRE, 2019). Most of the vacant office spaces are the ones developed in the outskirts of the main city making it less feasible for people to live there. If the area is secluded from the city, amenities are far off such as supermarkets, long transportation distances, etc. which make the embedment difficult for the people. (RVO.nl, n.d.). In such a case, entire system reuse becomes difficult and component reuse turns a viable option.

Figure 3: SUPERLOCAL Project, Source: Superlocal, n.d.

- **Component Reuse:** Product/component reuse implies the recovery of components from a building to be demolished and reuse it either on the same site or for a different building (Philip, 2001). A product has a lot more value than a material due to the investment of energy and labour deployed in the production process. Product reuse as a practice requires maintenance during first life, however later results in higher preserved value(Netherlands Statistics, 2019). It should not be confused with site relocation. Both reuse types have different requirements. For instance, in the case of site relocation, principles such as open building systems, modular designs, parallel disassembly and component identification are not normally relevant which are crucial for component reuse. Similarly, component reuse does not require a standard structural grid, on-site storage and spare parts as necessary for site relocation (Philip, 2001). Component reuse is easier in practice than building reuse. Following are some examples of component reuse:
- Utrecht Hofvan Cartesius is a circular business park where 90% of secondary materialsare used to convert 1450 m^2 of wasteland into circular hull pavilions, self-builds spaces and climate adaptive gardens with the reuse of rail tracks, hardwood doors, frames of the shed, wooden beams, etc.(Circulairestad, n.d.).
- Another example is the circular demolition of Erasmus MC's 80,000 m^2 of real estate which is to be demolished as it turned redundant for the advanced demands of the hospital and patients. It is now awarded for demolition based on criteria of circular demolition and the components deconstructed for reuse are sold to buyers arranged by the contractor (Madaster, n.d.). This study focuses on component reuse as it has higher value recovery than material reuse and is more likely than a building relocation/ building reuse.

Figure 4: Utrecht Hofvan Cartesius, Source: (Circulairestad, n.d.)

- **Material Reuse:** It is the least preferred type of reuse as the investment in terms of energy cost, labour and machinery cost that goes into raw material extraction, material production and manufacturing the product is wasted when it is reused at the material level. Materials are often reused by recycling them. However, recycling can preserve the value of the product only at the material level (Circulair, 2015). For instance, concrete which is responsible for 17 % of the total embodied energy in building materials (Herczeg et al., 2014), when crushed and recycled to be reused as a material, loses the energy consumed into manufacturing, transportation and delivery of the product. Additionally, crushing and recycling are also energy-intensive processes.

3.2. State of Art Reuse

The construction industry is not circular. Only 3%-4% of the total materials used are secondary materials (Michael, 2018). The reuse of building products in The Netherlands is characterized by lack of procedural guidance, weak engagement of stakeholders and absence of formal accounting (Icibaci, 2019). The existing method of destructive demolition does not allow for the retrieval of products and components for reuse(Tatiya, 2016). There is technological lock-in in the way buildings are traditionally demolished. It is carried out by medium and large scale demolition firms with equipment like pneumatic drillers, excavators and hydraulic hammers (Coelho & De brito, 2013). The reinforcement is recovered to be used as scrap while the concrete is crushed down. No attention is given to pre-demolition and waste management planning. The facility is demolished in a destructive way such that it damages the components and makes separation of material streams difficult (Michael, 2018).
Component reuse is a relatively new and complex process when compared to the straight-forward traditional demolition. To recovery components for reuse, it requires careful planning, execution and material handling. It is, therefore, a labour-intensive and time-consuming process. It costs more time and money than as the existing building stock is not designed to be deconstructed for reuse. It also depends on the economic aspects such as the presence of secondary markets, available building stock, etc.

State of the art deconstruction is limited to soft-stripping with simple tools such as sledgehammers, slitters and tip (Coelho & De brito, 2013). Applying the concept of the shearing layer of buildings by Stewart Brand, different components are locked in different layers of a building while in use. These layers include the stuff, space, services, structure, skin and the site (Stewart, 1994). Reuse is limited mostly to the stuff and service layer and somewhat to the skin (Philip, 2001). Mostly the materials recovered for reuse and sold in the market are installations, furniture and interior decorations in a process called soft stripping. Namely, electrical equipment, sink and sanitary basin, doors, windows, tiles, bricks. Small scaled demolition companies are called for this type of recovery called "manual demolition" whereas the medium-scaled firms engage in destructive demolition without component recovery for reuse (Coelho & De brito, 2013).

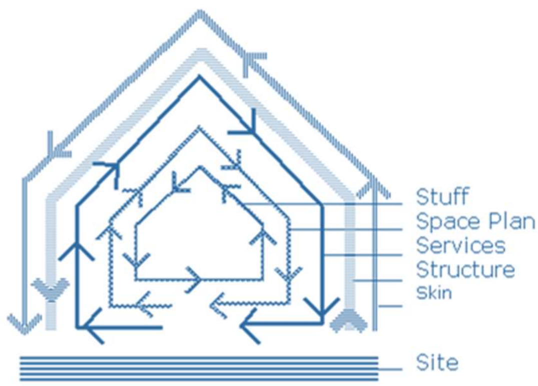


Figure 5: Shearing layers of Building, source: (Stewart, 1994)

3.3. Structural Component Reuse_ Current Situation

Reuse of structural element is very rarely seen in practice, especially for a whole concrete element. Although a building consists mainly of structural components yet the reuse of these components is yet not common as it is more complex and time-consuming to assess the quality of structural components than non- structural components (Bleuel, 2019). The structural layer consists of various components like beams, columns, walls, floors, foundations, etc. The reuse of these components is difficult but would result in high-value recovery. The general perspective of concrete and recycling industry is that concrete has the lowest reuse potential when compared to steel and timber (Hradil et al., 2014). Hence concrete components like floor slabs are seldom recovered for reuse.

Drivers: In the existing scenario, the drivers of structural component reuse are either a government law, agency, owner or a funding body. For instance, the drivers in case of the SUPERLOCAL projects are the municipality, housing association HEEMwonen and funding received from the government. Another example is the circular demolition of Erasmus MC's where the main driver is the EU public procurement laws for government institutions which dictates them to deconstruct for reuse. Funding from the government is also a big driver in reuse cases. Most of the pilot projects in the past for high-value reuse were subsidized by the government which covers the extra costs involved. For example, the CCE project (199-2000) was funded by the Alachua County Public Works Division (Bradley, 2004); the SUPERLOCAL project is supported by the EU funding, etc. At times collaboration of entrepreneurs, the motivation of the individuals and private investors also drive reuse projects, for example, Utrecht Hofvan Cartesius is one such case where the main drivers were the collaborative effort of entrepreneurs, private investors and subsidy from the municipality. The House of Rolf is a prototypical house which reflects the motivation of the owner of the house. The house was designed keeping in mind the available secondary products. It is completely made of waste materials from an old coach house to be demolished, for eg, load-bearing walls are made from the steel plates of radiators, the interiors are built with salvaged wooded interior(Architectuur.nl, 2015), etc.

Insights from Interviews

The reuse of structural components is not a common practice whereas recycling of waste post demolition is a common practice. It is the usual business to recover non-structural elements such as partition walls, floor tiles, doors, windows, furniture and roof tiles for sale. Rest everything is sent for recycling. Concrete is reused only on material level in new concrete and not on component level. The structural components if recovered are reused for non-structural purposes. For example, cast-in-situ concrete, huge blocks are cut out and reused for pavement for the new site but it is not being reused as a structural component. This way there is no need to test the components for strength. However, for the structural component, the only material deconstructed to be reused for structural reuse is the metal construction frame, steel structure. Hence, steel is more common than concrete for structural reuse.

But now the market is moving towards reuse and mostly all projects have a reuse part in one or the other form in it and it is becoming more common. The best practice is to investigate the building from top to bottom and aim for highest value recovery following the 7R model, to see if the building can be reused as a whole or take apart components for reuse or the least reuse at the material level. The last option to adopt should be demolition.

3.3.1. Why reuse structural floor elements?

Floors are planar structures and contain the maximum amount of building materials. The amount of concrete in columns and beams is significantly less than the amount of concrete in the floors. Hence, for the same building material, reuse of floor elements results in maximum value recovery in terms of embodied energy and embodied carbon deployed in their production. It also diverts the equivalently higher amounts of CDW away from landfills and recycling.

The geometry of floors allows for greater adaptability. Unlike floor slabs, stairwells, lifts shafts and roof components are often difficult to reuse (Glias, 2013). Other components such as columns and walls are often different in different buildings, affected by the changing floor heights. For instance, in 2004, the Dutch government revised laws regarding minimum floor heights. It implies that the columns and walls of older buildings are now too short to be reused in new construction (Dorsthorst & Kowalczyk, 2005).

There is also a higher level of standardization with the use of floors than other components. After the 1970s, most of the buildings in The Netherlands were constructed with prefabricated concrete components and the trend has continued to date as prefabrication allows for faster and cheaper construction (Bleuel, 2019). It implies that the existing buildings consist of a fairly good share of prefabricated floors allowing for greater chances of recovery. Since prefabricated elements are often standardized in dimensions, greater information can be availed concerning the slabs. Furthermore, there is lesser degradation on floors after use compared to exterior walls and exposed elements. The quality is maintained as the interior structure is not exposed to the environment.

Types of structural floors: The type of floor determines the method and equipment used to detach it from a building to be reused. Structural floor elements can be broadly divided into two types of floors: cast-in-situ floors and prefabricated floors.

- **Cast-in-situ**: It is the traditional floor construction where the slab is casted on-site with the framework of columns, walls and beams. In this case, deconstruction is often more challenging. A diamond saw is used to cut the floor slab and the dimension of the floor slabs is often according to the demand of the new construction. It is not preferred to deconstruct floor without a having a buyer as it requires further modifications as per the buyer's requirements once he is found.

- **Pre-fabricated floor slabs**: The floor slabs are manufactured off-site as independent units and then transported to be assembled on site. Prefabricated modular components are more suitable for reuse as they are the easiest to deconstruct, the process followed is simply that of reverse building construction (Dorsthorst & Kowalczyk, 2005). There are different types of prefabricated floor elements such as hollow core slabs, single- T slabs, double- T slabs, etc. The most common type of prefabricated concrete floor elements is hollow-core slabs (HCS) and double tee-floors (Engstrom, 2008).

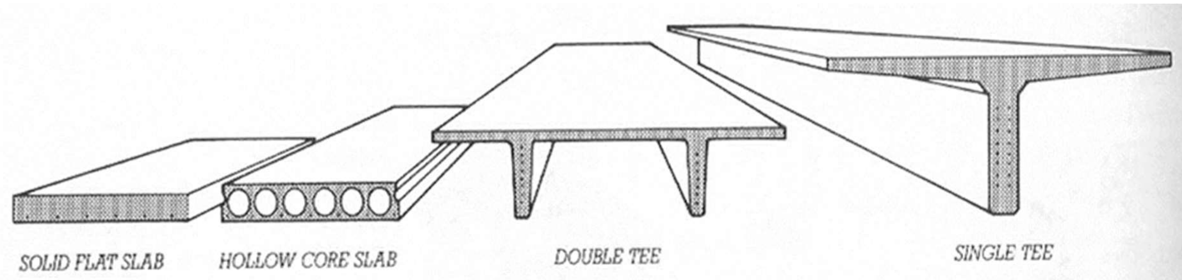


Figure 6: Most common types of prefabricated floor slabs, source (Levitt, 1990)

HCS is typically used in multi-storey constructions. The deadweight of the slab is reduced by providing tubular voids (with a diameter of 2/3 to 3/4 of the height of the slab) extending through the full length. The slab is typically 120cm wide. Single- Tee floor slabs typically have a deck surface about 1.5-2 inches thick and a concrete beam extending down from the deck surface along the longitudinal centre of the deck. Double- Tee floor slabs are the only floor slabs which can span over 16m. Double –T resembles two single T slabs put together with the deck cast as a single integrated unit. However, it provides greater structural capacity at longer spans than HCS. These slabs are more preferred over single- T. It has a standard width of 2400mm with a depth of 250mm-1000mm. Solid concrete slabs are generally called plates. They are heavier than HCS as more quantity of concrete is used. There are other floor systems which cannot be easily distinguished as cast-in-situ or prefabricated such as wide floor slabs, voided biaxial slabs, etc. These slabs can either be casted on-site or prefabricated off-site or a part of the floor is pre-fabricated and the rest of it is casted on site. From deconstruction point of view, they can be treated like cast in situ floors if fully or partially casted on site.

3.4. Why is reuse uneconomic?

To be adopted in practice, the economic cost of reuse must be cheaper than traditional demolition. There are various challenges which make recovery of products for reuse more-costlier than traditional demolition (figure 7). On average deconstruction costs approximately 26% higher than demolition (Tatiya, 2016). In projects where there is no subsidy or tax relaxation, it gets difficult to have a profitable business case. There are various reasons for reuse being costlier such as the lack of EOL planning, reverse logistics, market strategies, risk management for long term investments (Durmisevic et al., 2017), the uncertainty of demand and supply and the client's requirement of quick demolition (Michael, 2018). The greatest

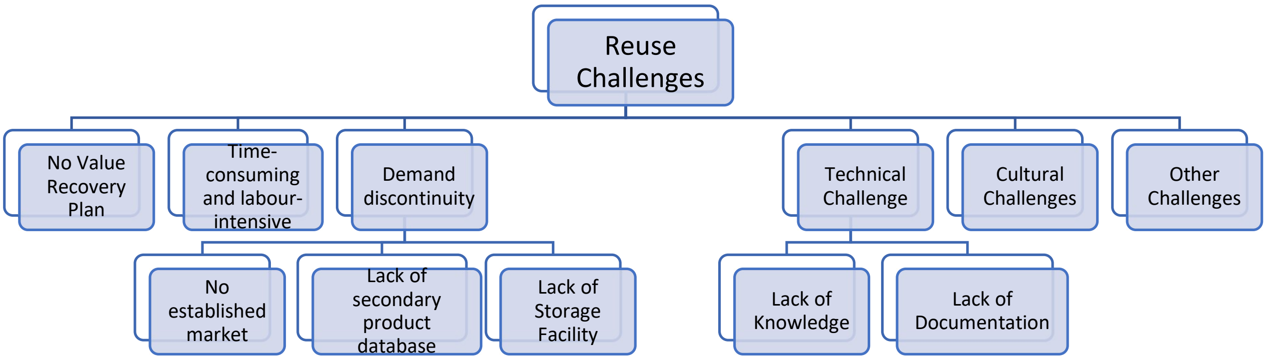


Figure 7: Reuse challenges, self-illustration

challenge for the reuse of panels and slabs is the deconstruction of these elements from the building followed by the lack of demand and market to sell them (Hradil et al., 2014). Each of these reasons are explained in detail below:

3.4.1. No Value- Recovery Plan

The value recovery after EOL is not a common practice in the building industry. EOL planning is often forgotten during the design and the use phase of a building. Value recovery is not included in the building life cycle. According to EN 15978, the last LCA stage is "Disposal" (figure 8). Value recovery with reuse, recovery and recycling is considered in module D as "supplementary information beyond the building life cycle" which are outside the system boundary. However, there is no clear rule for evaluation of module D (Hradil et al., 2014). Hence, it gets challenging to choose system boundaries for reuse. As a result, the building is demolished in traditional way without recovering value from the components. When buildings are not constructed for deconstruction as is the case for existing buildings, it needs to be very well planned during the use phase to analyze the various EOL options and determine the cost of

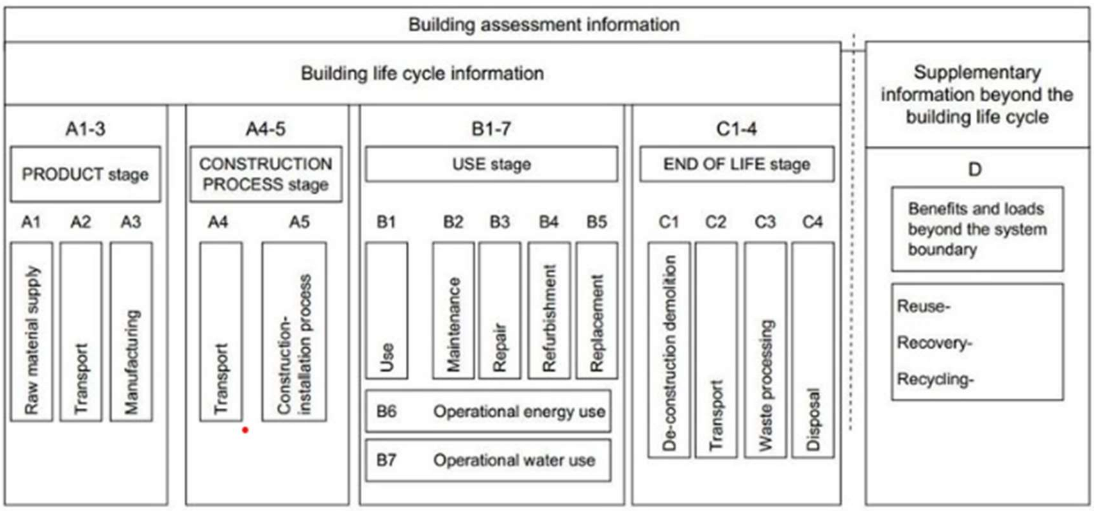


Figure 8: LCA stages of a building, according to EN 15978

recovering components for reuse. However, there is no tool or framework to quantitatively assess the economic feasibility of reusing components.

3.4.2. Time-consuming and labour-intensive

The deconstruction of the structure requires more time and manual labour to recover components for reuse (da Rocha & Sattler, 2009) (Coelho & De brito, 2013). Unlike in traditional demolition, deconstruction requires a detailed pre-demolition plan, thorough audits and inventory making of the products and materials locked in the building. However careful deconstruction often costs more time and cost overruns. For example, in the Udden Project, Sweden, 50 large apartments were deconstructed to build 22 smaller ones. Since the walls and beams were casted-in-situ, they were carefully separated using a diamond saw. As a result, there were time overruns which eventually lead to cost overruns and termination of working contracts between material suppliers and users. There were 10-15% extra costs which were compensated with governmental grants (Eklund et al., 2003). For deconstruction, a greater number of skilled workers are needed having the knowledge, experience and skill to carefully dismantle the component for reuse. Deconstruction of an average house can take 5-6 workers for about 10-15 days whereas it takes only two days with one worker to demolish the same (Tatiya, 2016).

3.4.3. Demand discontinuity

Continuous demand for secondary material is crucial for making reuse a successful practice. At the moment there is a high inconsistency of demand for secondary components. About 1/3rd of the waste arriving at recycling facilities is reusable and can be sold second-hand(Commission European, 2019a). However, the market for structural secondary products is yet not established (Glias, 2013). There is a market for the non-structural components only like windows and doors (Bradley, 2001). Due to this variable supply, secondary components cannot be circularly procured. Other reasons for demand discontinuity are the lack of secondary product database and storage facilities to store these products.

- **No established market**

The presence of a local reuse market is crucial to maintain demand consistency. The absence of such market results in higher transportation costs and total reuse cost (Tatiya, 2016), (Bradley, 2001),(Dijk et al., 2000), (Philip, 2001). When there is no market for secondary components, the reusable components despite being cheaper than the new materials are demolished. For example, in a project “Recycling prefabricated building components for future generations”, Germany, the secondary components were 50% cheaper than new ones. However, due to the lack of secondary markets and demand for recycled crushed stones, even the easy to dismantle buildings were demolished (Glias, 2013).

In the past, there have been attempts to commercialize the market for secondary materials but without any success. All efforts in this direction have collapsed due to lack of funding and expected revenue streams. Around seven private firms tried making joint reuse platform but soon dissolved (Icibaci, 2019). Although there is no consolidated sales platform, there are online market places for advertisement and sale of secondary materials such as insert.nl, gebruiktebouwmaterialen, Marktplaats, Bouwmarktplaats, Excess Material Exchange (EME), etc. Online platforms such as the “Oogstkaart” developed by Superuse studios provide information of the residual materials on a geographical map for reuse (Superuse Studios, n.d.). However, a deeper look into the online platform shows that the material advertised are only the products of soft-stripping such as the wooden panels, roof tiles, glass, electrical installations, etc.

- **Lack of secondary product database**

For reusing structural components, it is imperative to create a detailed inventory of the products to share with the buyers. A product database or the material passport contains the quantities, sizes, type, age, strength and other relevant information of the component.

However, there is still no central database for existing building stock. As a result, it is hard to estimate the value of the secondary component. If a centralized database is created, it can help match the demand of new building with existing stock, hence reducing the demand discontinuity and eventually the cost of procurement by procuring from closer buyers. There have been efforts to create a central database. For example, "Building As Material Banks" which is a horizon 2020 projects which aim at reducing waste and use of virgin materials by developing buildings passports and making material databases (Debacker & Manshoven, 2016). The project is not specifically oriented to promote reuse but will help in identifying reusable materials, quantities and qualities.

- **Lack of storage facility**

Storage of secondary component requires space and costs money to the owner. Space is either rented out or owned by the owner who needs to pay the operational costs. Hence, the owners do not prefer to deconstruct a component if there is no buyer in advance. It then adds to discontinuous supply as there remains no backup stock to feed the construction demands.

3.4.4. Technical Challenges

There are various technical challenges which make structural component reuse uneconomic as listed below:

- **Lack of knowledge:** the knowledge on the process and technique of deconstruction is meager which leads to time and cost overruns. When the labour is not trained to deconstruction or doesn't have the experience, the chances of damage to the components are higher resulting in greater repair costs or even the loss of component. Other processes such as efficient site logistics, cataloguing and testing for quality are fairly unknown as well.

- **Lack of documentation:** The lack of proper documentation further creates issues such as legal uncertainty about the quality and performance of the product (Commission European, 2019a), (Durmisevic et al., 2017). Old buildings are seldom documented and the ones which have some drawings are often not updated leading to design inconsistency. For instance, during the Maassluis project, The Netherlands, the deconstruction started following the details from the structural drawing. During deconstruction, it found that the details on site did not match the ones in drawings, leading to difficulty in dismantling and damaging the components. Furthermore, the harder mortar in the connection between floor and column of the precast system (elementum) caused the entire building to move out of plumb (Dorsthorst & Kowalczyk, 2005).

3.4.5. Lack of Policy framework

The performance of the components needs to be assured by testing their quality in compliance with standards for engineers to reuse them (Michael, 2018). However, there are no guidelines in the building codes for reuse. Furthermore, there is no method of certification and warranties of the secondary components. Re-certification of the components in most of the cases is not possible (Michael, 2018). Due to the non-binding nature of the existing guidelines for reuse, they are hardly followed. The existing policies directed towards resource efficiency do not give explicit reuse targets to be met. For instance, the "EU construction and Demolition Waste Management Protocol, 2016" which is a set of non-binding guidelines which encourages practice like the undertaking pre-demolition audit to be carried out before any demolition or renovation project to identify the quality, quantity and location of the materials in the building and gather information on which materials can be reused/recycled. It further advises that the audit be carried out by qualified expert with knowledge of building materials, demolition techniques and local markets. Another recommendation is to develop a waste management plan containing information on different steps of demolition, material separation, handling, transportation and final disposal (Commission European, 2016). As a result of lack of concrete tragets and policies for reuse, the structural component reuse is not practised and continues to be an unknown process with greater risks and higher costs. To facillitate reuse and understand the reuses costs better, it should be supported by concrete policies.

3.4.6. Cultural Challenges

The cost of reuse also depends on the revenue earned from the sale of the component. Higher the revenue, lower the costs and more profitable the business case. The balance of supply and demand is further influenced by the changing trends and preferences of the users. For instance, there is a decrease of traditionally built houses in The Netherlands which implies a decrease in demand for secondary wood in the future (Icibaci, 2019).

There is also a reluctance on the part of the consumers to use secondary components. They are often not willing to pay even 50% of the price of the original product. Cecilia Gravina describes three kinds of buyers: low-income buyers who buy large quantities at cheaper prices, medium-income buyers who pose specific performance requirements and high-income buyers looking for the aesthetic and antique value of the product at a price higher than the new product. There is also a new emerging class of customers emerging called the "green clients". These are the clients who are committed to environment friendly construction and promote the use of salvaged products (Bradley, 2001). However, this trade is not scaled enough to the level of structural building elements.

3.4.7. Other Challenges

It includes the low cost of new materials which makes reuse more expensive. For instance, in the Middelburg Project, The Netherlands, seven floors of a residential building were disassembled and reused to build two apartment buildings. The construction was demountable with dry mounting connections of steel strips and bolts (BMB system), Each component was provided with a code and the new building site was used as storage site to maximize the efficiency. But when compared to the cost of building with new components, the reuse project was found to be 18.7% more expensive (Dorsthorst & Kowalczyk, 2005). Another factor is the time or the service life for which materials are locked in the buildings. The time is long enough such that when the product is available for recovery, it has to compete against newer, cheaper and certified alternatives in the industry (Icibaci, 2019). Furthermore, the consumption of CDW by the road industry makes traditional demolition more attractive than deconstruction. Other process costs such as the cost of transportation, storage and testing further add to the reuse costs (Michael, 2018).

4

DECONSTRUCTION FOR REUSE

This chapter elaborates the process of deconstructing a building to obtain components for reuse. First the deconstruction process is compared to the traditional demolition in terms of the stakeholder network, thereafter the difference is emphasized based on the labour requirements of the two process. Lastly a detailed description of traditional demolition and the process adopted for deconstructing a building are explained. This chapter answers the following research sub-question:

Q3. What is the process to deconstruct a building for reusing components? How does it vary from traditional demolition practice?

4.1. Actor-Network

Component reuse is a complex process and involves many stakeholders unlike the straight forward traditional demolition. In traditional demolition, the building owner hires the contractor for demolition who demolishes the facility, the debris is then transported to the waste collector who treats it. However, in a deconstruction project, there are many actors which directly or indirectly influence the process. The dialogue and understanding amongst these stakeholders

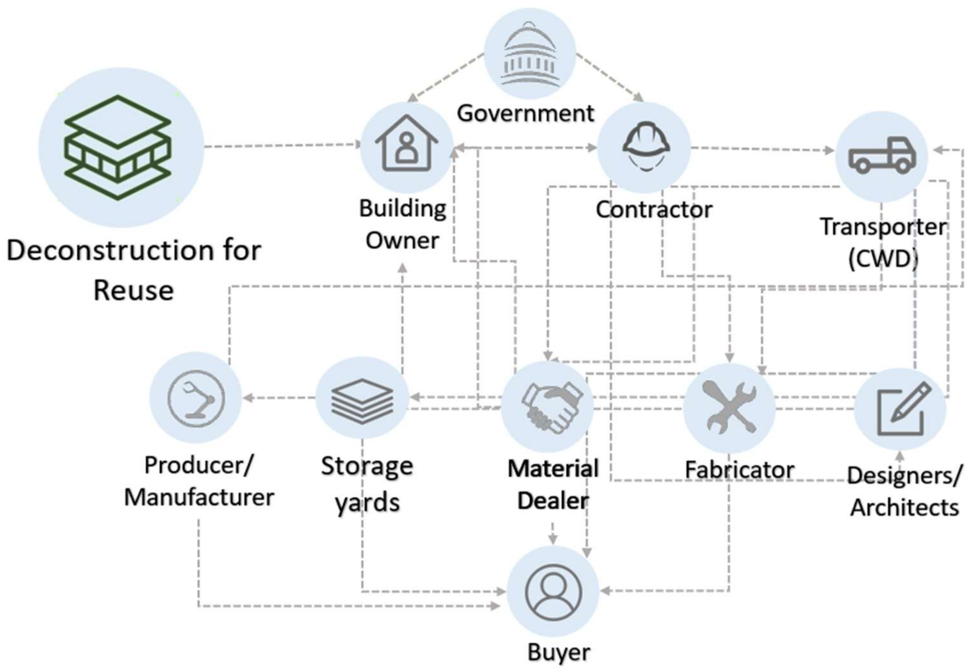


Figure 9: Deconstruction Actor-Network, self-illustration

are crucial to make reuse practical and scalable. Two tiers of stakeholder can be identified in the literature. Tier one stakeholders are directly involved in the process of reuse such as owners of the building; demolition contractors and CDW transporters (Coelho & De brito, 2013). The second-tier stakeholders are the governments, producers, manufacturers, architects, designers, material dealers and end users that have an indirect influence on the practice of reuse.

- **Building Owner**: The owner of the building can be an individual, municipality, real estate developer, etc. Owner's motivation and willingness to deconstruct the building for reuse is a pre-requisite for reuse. The question has to come from the owner to deconstruct, only then a contractor will go for deconstruction instead of demolition (Interview 01, 2020). No contractor takes up a voluntary job to reuse when he is asked to demolish as it costs more time and money. If the owner does not allow for sufficient time to deconstruct and puts strict time constraints on the contractor to clear the site quickly, the contractor goes for demolition to deliver in time (Interview 02, 2020). The owner, although an active stakeholder does not take much responsibility when it comes to finding buyers and potential clients for the secondary products. The demolition contractor or the retail firm is held responsible for it while the owner wants quick clearance of the site. For instance, in case of Erasmus MC, the representative from Erasmus MC cleared how direct sales or finding buyers is not their approach and held Dusseldorp (demolition contractor) responsible to find buyers itself (Madaster, n.d.).
- **Demolition Contractor**: The demolition contractors/firms are assigned the contract to either fully demolish, partially demolish or fully deconstruct the building for reuse by the project owner. The contractor is then held responsible for the removal of the building and handling the EOL materials released.
- **Architects and Designers:** They have an important role to play. They must design the buildings with the knowledge of existing building stock such that existing secondary components can be reused in the construction. They should be aware of the supply of secondary components, their performance and dimensions and be flexible to design for reusing them (Hradil et al., 2014), (Michael, 2018).
- **Material Dealers:** Also referred to as retailers, they procure secondary components from demolition contractor and then sort, grade, batch and sell the components to end-users or back to the manufacturers. However, the network of such retailers is established mostly for the products of soft-stripping and not much for structural elements.
- **Transporters**: The products recovered for reuse are transported by the transporters either to a construction site, a secondary product end-user or a storage yard.
- **End-User:** End-users/clients of products obtained from soft-stripping are typically either be low-income buyers who buy the products at a lower price and lower performance; medium-income buyers who use the products for replacement in existing buildings or high-income buyers who buy products for their aesthetic value at high prices (Coelho & De brito, 2013). For structural components, the end users are mostly builders or contractors who wish to procure secondary components.
- **Producers and manufacturers:** They should design for disassembly and enable take-back of their products from buyers and clients after EOL.
- **Government:** Government plays a vital role by providing grants, subsidies and tax relaxations to pilots project (Macozoma, 2001),(Glias,2013), (Bleuel, 2019). In projects where there is no subsidy or tax relaxation, it gets difficult to have a profitable business case. For example, in the Maassluis project, The Netherlands**,** 4-floor high apartment buildings were reused by removing the top two floors and renovating the rest into single-family dwellings. However, since there was no subsidy from the government, all the risks were directed to the housing association and contractor (Dorsthorst & Kowalczyk, 2005). Policy regulations by the government on waste disposals and resource recovery can substantially influence the cost of reuse. The case of Erasmus MC is a classic example of the impact of law and policy instating deconstruction instead of demolition. Furthermore,

there should be specific guidelines for material grading and testing of secondary components.

Insights from Interviews: The type of legal contract between the actors determines their roles and responsibilities. The contract also defines which actor owns the secondary products after deconstruction. Currently, the demolition contractor claims the products and sells them himself. The owner of the building wants the site clear quickly and does not want to find buyers himself.

4.2. Labour Requirements

It is established from literature and interviews that more labour is needed for deconstruction, however, there is no concrete figure as to what greater percentage of labour is needed. Findings from the literature suggest that 5-10% more labour needed for deconstruction than demolition (Michael, 2018). Demolition is mainly a mechanical process and requires a maximum of two workers, one to operate the crane and the other on the ground to handle the debris whereas deconstruction for reuse is a labour-intensive process. It requires a mix of 4-5 skilled and un-skilled labours(Bradley, 2001), (Interview 02, 2020).

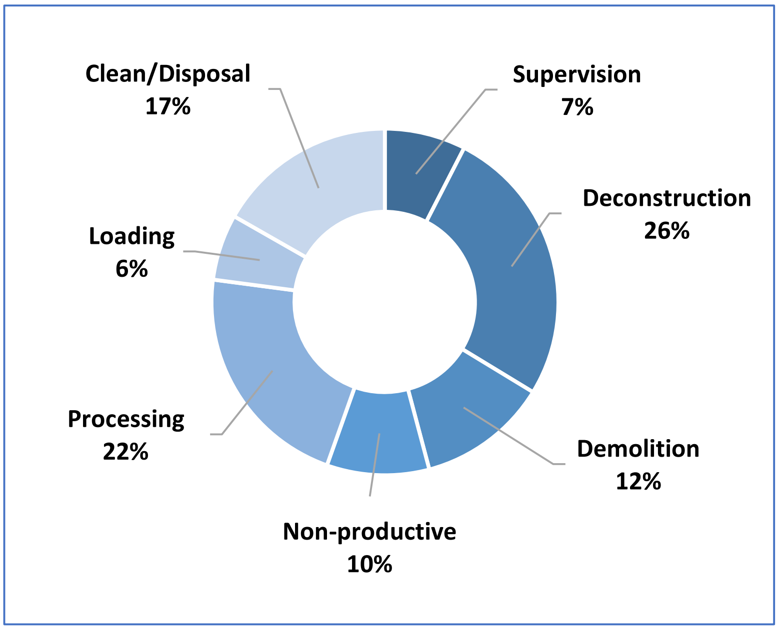


Figure 10: Average Labour Time(%) by work Categories,(Bradley, 2004)

Unlike demolition, labour performs various activities in a reuse project. The process of retrieving structural components for reuse requires skilled labour. They should know how to remove the product without damage, distinguish and effectively separate the salvage products from those to be demolished, recondition them on-site, be aware of the critical building supports to prevent sudden collapse accidents. etc. Guy Brandley researched the work categories performed by labour in terms of the percentage of time spent on each activity (figure 10). The categories include supervision (directing the flow of work on-site), deconstruction (the removal and direct handling of a material), demolition of remaining structure which is not deconstructed, processing (preparing for reuse, eg, de-nailing), non-production (no work occurs such as breaks and equipment cleaning), clean-up or disposal of debris and loading of materials. It can be noted that the largest time is spent on the deconstruction process about an average of 26% of the total time followed by processing (Bradley, 2004). However, the labour hour per activity can vary depending upon the situation. For instance, when there is very short time available for deconstruction, the maximum labour is diverted into deconstruction (47%) allowing little time for other activities such as modification/process of the elements or careful loading. Similarly, when the salvage value of secondary components is low or the quality is more, more effort is diverted into disposal and cleaning (40%) than in other processes.

Insights from the Interview:
Demolition is a much faster process than deconstruction. A building can be demolished at a rate of about 250-350 m2 a day, with a maximum of 2 labour and a 20-40 ton crane whereas for deconstruction you need about 4-5 labour on site instead of 1-2 and an extra crane to lift the heavy floors. Time-wise the deconstruction would take about 50-100 m2/day as now you

have to be careful to take out the elements with care. There is an order to dissemble unlike in demolition where the aim is to break the critical points and bring down the building. If the firm is well experienced with the method, the fastest they can deconstruct is a 150m2/day.

4.3. Traditional Demolition

Traditional demolition is the process of turning down the building with destructive methods. The technique and sequence of demolition depend on the construction material of the building i.e., buildings with brick construction, concrete frame or steel frame. Manual and mechanical are the two main types of demolition. While manual demolition is mostly seen in small houses with cheap labour, mechanical demolition is the most prevalent one.

Labour and machinery: Demolition is a relatively simple and quick process. It is mainly carried out with machines and does not require much time or labour. Only one worker is needed to operate the crane and another is stationed at the ground to handle the debris. The speed of execution is about 250-350 m^2 in a day with a 20-40tn crane (Interview 02, 2020). The total labour hours depend on the size of the project. A small or a big project is not determined based on the turnover but on the time required to demolish it. A small project has 3-4 weeks demolition time, 4-10 weeks for a mid-size project and a big project is above 10 weeks. The structure is turned down using breaking shears, pneumatic breakers, rams, wrecking ball, excavators, bulldozers, etc. For higher floors, a 40-ton crane with a long arm is needed whereas for lower floors a 40-ton crane without the long arm is used. Furthermore, a crasher is needed in case the concrete and steel are separated on-site and sent directly for recycling.

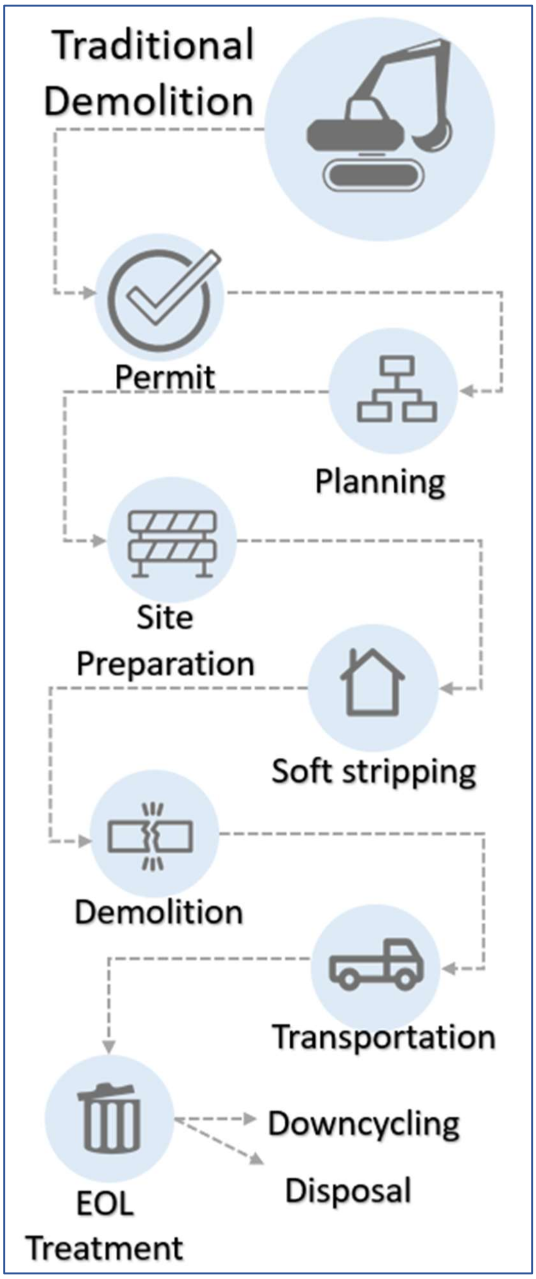


Figure 11: Traditional Demolition Process, Self-illustration

Process of Demolition

Figure 11, shows the process of traditional demolition.

The first step in the traditional demolition process is to obtain the demolition permit from the concerned authorities following which the planning stage starts. It involves site visits, making demolition schedules and waste management plans. Thereafter, the site preparation begins such as installing the site hut, toilets, safety lines and safety nets. Thereafter, the site is investigated for the identification and removal of hazardous materials such as asbestos, lead paint, etc. Then commences the soft-tripping to recover the valuables from temporary layers of the building such as sanitary wares, doors, windows, floor covering and ceiling plaster, glass from windows, service installation, piping, roof tiles, etc. The products of soft-stripping are easy to sell as there is a market for them already. Hence it is a common practice to recover these before demolition. It is also called as the non-structural deconstruction as it involves removal of non-load bearing components (Bradley, 2001). It can be done with simple

tools and unskilled labour. Soft-stripping is carried out by first removing the heating components, doors, windows, shutters and sanitary ware. Thereafter, coverings of the floor, roof and walls are stripped followed by recovery of electrical, sanitary, plumbing and heating installations. Lastly, roof frames and wall insulation materials are stripped before starting to deconstruct or demolition the building (Michael, 2018). The waste produced during this stage is mixed and is send to sorting plant where it is separated into burnable and non-burnable (Dijk et al., 2000).
After soft-stripping, the demolition begins from the top to down i.e, starting from the roof generating huge amounts of debris.

Apart from creating unsorted debris, mechanical demolition leads to health hazards such as dust production, noise pollution from the machine, etc, affecting the workers as well as the people in the neighbourhood (Tatiya, 2016). Thereafter, the debris is transported for disposal as explained below.

- **Transportation of the debris**: The mixed debris can either be separated on-site by the demolition contractor or sent to a local waste collector/ crusher (sorting company). Some of the big demolition contractors also have their processing units where they break and separate the debris and send it for recycling or reuse in the road industry. For on-site separation, the debris is separated, reinforcement is recovered and sold in scrap and remaining rubble is sent for end treatment. It has been pointed out during the interviews that it is not always that the scrap is separated from the concrete. It depends on the amount of steel and the size of the project. About 2% of the total debris is steel but the steel from floors is hardly extracted for selling in the scrap as it is thin and broken by the shears in demolition (Glias, 2013). On-site separation saves the extra transportation and storage costs but demands proper material handling and space for segregation on-site. If the debris, contains non-reusable and non-burnable materials, the demolition contractor stills need to get it certified from a sorting company before transporting it to the landfill site. This leads to a significant increase in the costs making separation on site less attractive (Dijk et al., 2000). The alternative is to send the mixed waste to a regional waste collector, who then segregates, sorts certifies and sends the waste to the final processors such as recycler, incinerator or landfill operator. It is a costlier option since the heavy fee of about 90 euros/ton is charged by the collector (Icibaci, 2019).

- **EOL treatment of the debris** - Disposal costs constitutes 15% of the total deconstruction cost (Tatiya, 2016). There are different ways to dispose of the debris:
    1. **Reuse in the road industry:** It is the most popular way in the current practice. About 95% of the total C&D is treated in this way. The debris is sold to the road industry where it is used for constructing road-subbase, it generates revenue at 4.5 euros/ton of debris for the demolition contractor (Icibaci, 2019).
    2. **Recycle for new concrete**: The debris is crushed and washed thoroughly to obtain the aggregates to be reused in new concrete. It requires the installation of a recycling plant or can be alternatively be taken to an existing facility. It generates revenue since the secondary gravel is then sold for the production of new concrete.
    3. **Landfilling:** Landfilling was a common practice before 1993. The burnable CDW was often landfilled since the landfilling charges were lower than incineration charges. (Dijk et al., 2000). It was only after the landfill ban that the operators started charging gate fees. Gate fee is the landfilling tax or the tipping fee paid at the landfill site. Landfilling is banned for most of the waste in The Netherlands but for other wastes, it is 13 euros/ton (Eurostat & Deloitte, 2015; Michael, 2018). The ban promotes the reuse at the material level where the residues such as pre-crusher fines are separated into fractions leading to a significant reduction in the volume of the waste to be landfilled. Now the operators accept residues only from certified companies which give landfill mark ensuring that the residues contain no more than 12% reusable materials.

Insights from Interviews
Out of the total debris, about 90% is sent for reuse in the road industry, the remaining 10% is mixed waste which is sent to collectors such as Renewi (Interview 03, 2020). Currently, a very little fraction of the debris is sent for landfill. Mostly the contaminated fraction having asbestos and sometimes mineral wool is sent for landfilling (Interview 04, 2020).

4.4. Process of Reuse

The process of reuse can be broadly studied in three chronological stages: deconstruction stage, material handling stage and consumption stage as shown in figure 12. Each consecutive stage begins only after the completion of the preceding stage, i.e. material handling starts after the deconstruction and before the consumption of the secondary components. As the names suggest, these stages are indicative of the processes carried out within the respective stage. Each of the stages is explained in detail in the following section. It involves various additional activities spread over different stages of execution.

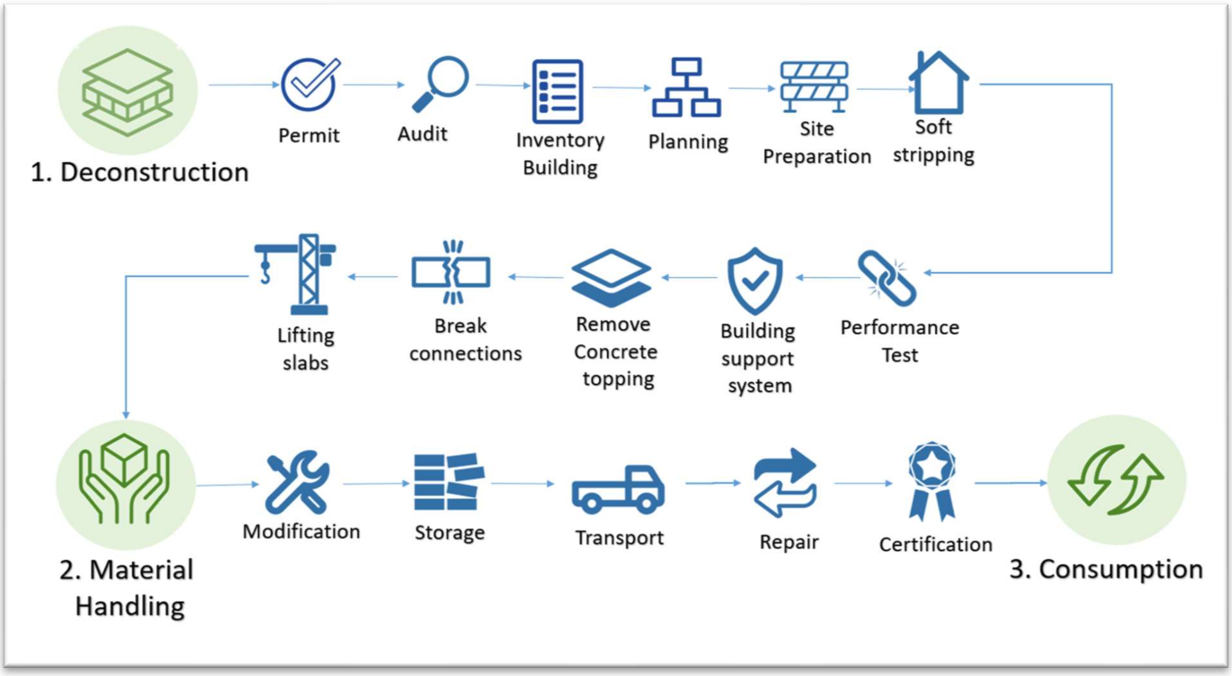


Figure 12: Process of Component Reuse, Self-Illustration

4.4.1. Deconstruction Stage

Deconstruction is the process of the selective and systematic dismantling of the building to salvage products for reuse such as the building frame, the roof system, floor and walls. It is not only an effective technique of building removal but also a high-value waste management strategy as it directs waste away from the landfill site, saves virgin material extraction and conserves embodied energy. Although deconstruction is more beneficial, it is hardly practised due to its complex nature, skilled labour requirements and time-consuming operation (Tatiya, 2016), (Bradley, 2001). In the Netherlands, there are as such no special techniques for the deconstruction of the concrete and masonry buildings, the techniques are the same as those used for demolition (Dorsthorst & Kowalczyk, 2005). It is simply carried out as 'construction in reverse order" (Bradley, 2001). There are two processes involved in the deconstruction stage: preparation to deconstruct and execution/disassembly.

1. Prepare to Deconstruct

As shown in figure 13, the process “prepare to deconstruct” consists of sub-processes most of which are performed in traditional demolition as well. Each sub-process is dependent on the completion of its precedent, it can be executed once the previous process is completed.

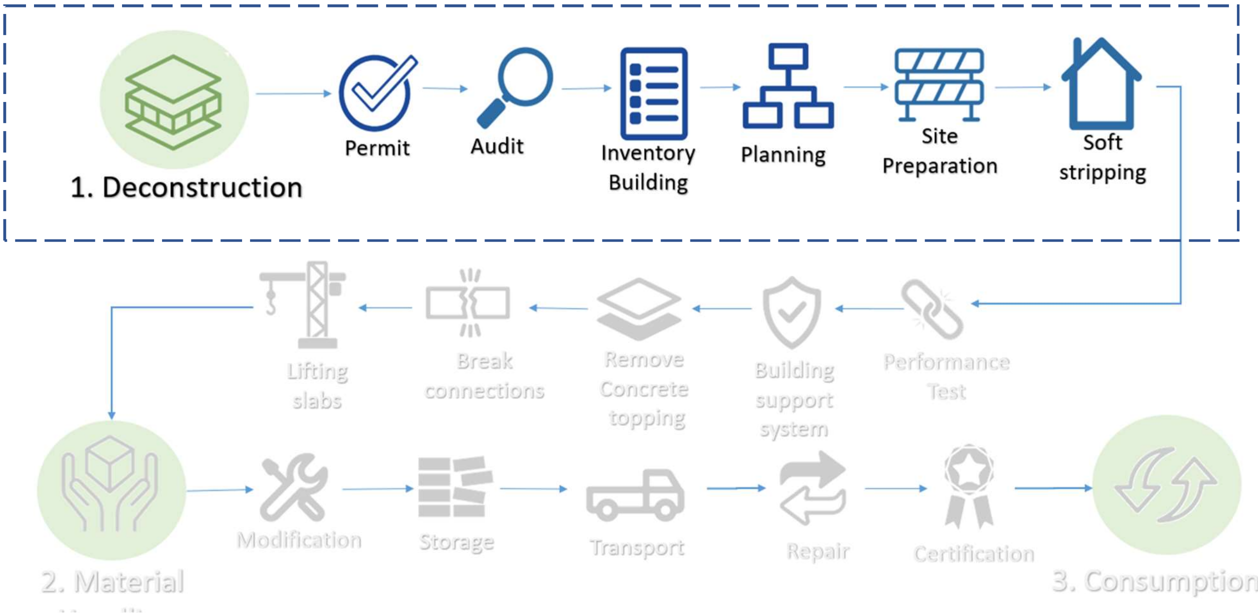


Figure 13: Preparatory steps to deconstruct, self-illustration

- **Obtaining a permit**

Like in the demolition process, the first step in a deconstruction project is to obtain a permit to carry out the job. The cost of obtaining the permit is the same for deconstruction as it is for demolition (Bradley, 2004).

- **Audit**

An audit is defined as a systematic and documented process carried out to obtain records, facts and other information and objectively assessing them against specified requirements (ISO, 2004). For deconstruction, the intension of such an audit is to check the quantities, physical conditions and the location of the components in the building for reuse. It is conducted in two stages: the first stage starts with the review of the available documents such as engineering drawings, building models, etc. Thereafter, in the second stage, a physical examination of the building is to be carried out by an expert. This practice is common for both demolition and deconstruction practices; however, it is more intense and detailed for deconstruction.

- **Inventory Building**

An inventory is an extensive list containing information on the quality, condition and quantity of the secondary products (Michael, 2018). Inventory building is the process of documenting the findings of the audit. It contains detailed information on the type of components, quantity and quality, accessibility for equipment and presence of hazardous materials if any (Tatiya, 2016). This information can comprehensively be presented in the form of a certificate called Element Identity (EID) for each component (Glias, 2013). However, there is no standard format on how to build such an EID and what information it should contain. Hence, the format and content of EID vary for each building.

- **Planning**

Having identified the materials and components in the building, planning is done to efficiently take them out of the building. A deconstruction plan is drafted followed by a waste management plan. An additional yet important step is to find potential buyers for secondary products.

- **Deconstruction Plan:** it is essential to have this plan in place. Although it costs time and money to make the plan, it reduces the landfill costs (Dorsthorst & Kowalczyk, 2005). It includes the planning on the method of deconstruction, site management, scheduling and sequencing of tasks. The site layout should be so drawn that there are no conflicts concerning the available time and space allowing for efficient stripping, de-nailing, cleaning, sorting, sizing, bundling and stacking (Bradley, 2001).
- **Waste Management Plan**: Waste management plan is made to decide the EOL treatment of the debris as to which materials are recycled or landfilled and what routes are they directed to. In the case of deconstruction, there remains a fraction which is demolished as 100% recovery for reuse is very rare. The components which are either deteriorated, have low salvage value or no market for sale are often demolished. Waste management plan dictates the handling of this waste stream.
- **Find buyers**: It is a very crucial step for effective reuse. It is always preferable to have a buyer in place before starting to deconstruct to reduce the additional handling costs of transportation, storage, etc. However, in case there is no buyer beforehand, the advertisements and campaigns are started from the planning stage to investigate the secondary product markets, determine the demand and find a suitable end-use for salvaged components. The product information documented in the EID is used for this purpose. Another task at this stage is to determine the resale value of salvaged products, the associated costs of storage and transportation (Bradley, 2001). These costs will be discussed in detail in the next chapter.

- **Site Preparation**

The site needs to be prepared before starting the deconstruction work to ensure smooth material removal, processing and storage within the available space. It includes clearing up the space for equipment access, installing required safety measures like barricades and scaffolding, setting up recess huts, mobile toilets, etc. Another important step in the site-preparation is detoxification. Before deconstructing or demolishing the building, it is important to remove any hazardous material present in the building. These are materials such as asbestos, lead in paints, oil tanks, contaminated soils, etc. The presence of hazardous material in the building makes demolition more expensive as it needs careful planning and execution to take this material out safely. The asbestos analysis is carried out by a certified company which removes any asbestos present as per the Asbestos Removal Decree (Dijk et al., 2000).

- **Soft-stripping**

Soft-tripping is done both for demolition and deconstruction and mostly in the same way. Soft-stripping should be performed only after the EOL decision is taken. In case of demolition soft-stripping can happen immediately before demolition, however, for if the decision is pending for deconstruction or the owner is searching for buyers, it is wise to keep the exterior envelop intact as it protects the elements from external environmental damage.

2. Execution (Disassembly)

Disassembly is the process of recovering the components with minimum damage and maximum reusability. To measure the reuse potential, disassembly needs to be assessed (Durmisevic et al., 2017). The ease of disassembly depends on several factors such as the method of construction, the type of connections between different components (dry or permanent), etc. These factors will be dealt with in detail in the reuse feasibility chapter. Disassembling starts from the top to down, i.e. the roof of the structure. First, the floor slabs are removed, following which the façade beams, beam, column and wall elements are removed (Glias, 2013).

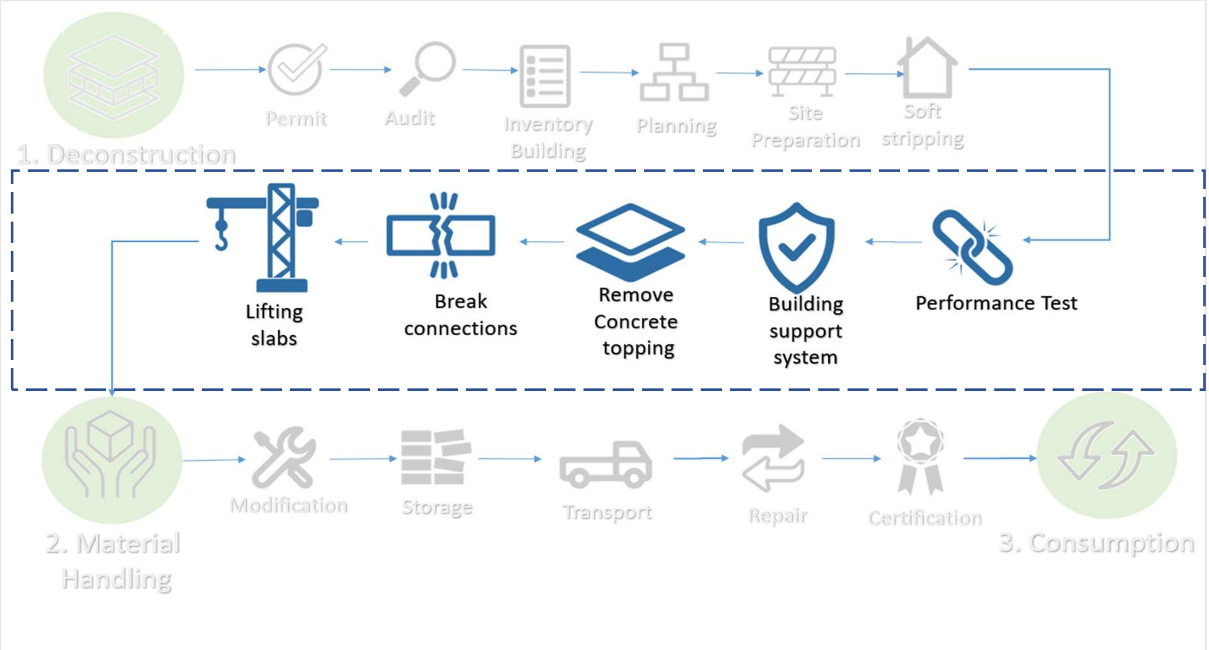


Figure 14: Execution Stage of Deconstruction Process

Following steps are followed to disassembly structural floor elements (figure 14):

- **Performance Test**

After the building is stripped to its structural skeleton, performance testing should be carried out to ensure that the structural floor elements are durable enough for reuse. Testing is also done to confirm the consistency of design on the drawings and as-built on site. During the use phase of a building, there are renovations and changes made to the structure which are not documented and therefore tests are conducted to ensure what's on the drawing matches with what's inside the structure. However, such changes are rarely made to the structure of the building, especially the floor elements.

The performance testing is done either by a first part conformity assessment method or second party conformity assessment conformity method. In first-party conformity assessment, the person or organization carries out in-house testing themselves whereas in second party conformity assessment the assessment is done by the end-user himself (ISO, 2004). The level of performance testing needed for a salvaged product depends on two facts: the presence of documents which contain performance details of the components and the requirements of the client/end-user as to how much assurance he wants on the product.

o **Level 1_Visual inspection**: it is the examination of the concrete floor slabs after soft-tripping when the surface is visible. It is carried out by an expert the assessment is based on his professional judgement. However, one can question the credibility of such a judgement as there is no guideline on the subject of qualification requirements of an expert to assess secondary building components. Level 1 is sufficient in cases where the documents are available plus the client does not demand further testing, often when the owner of the building reuses the components himself.

o **Level 2_ Non-destructive testing:** In the case of indoor concrete elements, the service life is as high as 200 years with no damage conditions. However, if visual degradation is identified during inspections, further testing is needed. The non-destructive tests like the rebound hammer, probe penetration, pull-out, ultrasonic pulse velocity, etc can also be used but the results are relatively less accurate (Glias, 2013).

- **Level 3_ Destructive testing:** Often when no information is available about what's inside the floor and/or the results of non-destructive tests are not aligned with what's there in the documents, destructive testing is done. It can be observed as a first-party or second-party conformity assessment. Third-party involvement is recommended to ensure unbaised test results. The destructive tests are performed at critical spots only. In the case of concrete elements, the tests generally conducted are for carbonation, compressive strength with concrete cores, the position of reinforced steel and bearing capacity.

Insights from interviews:
Following trends are observed in practice:

- There is no performance testing protocol in place which clearly states the description of quality tests. It depends on the requirements of the end-user and the budget for testing.
- First-party conformity assessment is not done as it would mean that the demolition contractor tests the performance himself. However, second-party conformity is sometimes done when the end-user wants to tests himself for quality. The contractors ask the buyer to come to the site to look at the components and assess the quality himself if he wants (Interview 05, 2020). Sometimes when the reuse is for the same owner, then assurance need not be so strict otherwise you have to involve an authorized third party for testing the elements (Interview 07, 2020).
- The tests performed on secondary concrete slabs are low-level basic tests but the dimension of the slabs is huge which makes the testing complicated. No accreditation of the laboratory is needed to perform them. Concrete floors slabs are tested according to EN 13791 for strength by drilling cores, EN 1168 full-scale test for shear resistance, carbonation depth, etc. Testing is only needed if there is no historical data available. If a good historical data of the components are available, only visual inspection of the slabs is needed, not destructive testing. It is easy to get a good idea of loading conditions of a building built as per standards. However, the problem arises when a building is older than 50 years. In such a case testing is useful.
- Cost: The prices depend on the number of samples and also on the condition of the slabs. EN 13791 gives indications on the number of tests required. The cost of testing cores is about 100 euros per core, full scale testing costs about 500 euros per slab. Drilling is the most expensive part as it costs about 2000-3000 euros a day (including supervision).

- **Building the support system**

Before starting to separate the floor elements, it is important to sufficiently support the elements to avoid unexpected collapse. Propping, bracing, shoring and scaffolding systems are erected to ensure the stability of the structure and safe movement of workers. Supports are created for the walls and columns with shores below the floor to be dismantled.

- **Remove concrete topping**

The surface of the floor slab is not accessible as it is covered with a topping layer. It is a homogenous continuous layer in case of cast-in-situ floors. However, for prefabricated floor elements, the toppings are of two types (Glias, 2013):

- **Concrete Compression layer**: This layer connects the slabs with reinforcements (figure 15). It has a minimum thickness of 50mm. For the disassembly process, this layer is removed and poured again when the slab is reused. Not removing the layer only increases the dead load of the component as it loses the function of lateral load transfer once the reinforcement is cut at the joints. It is removed with a compressor and hammer.

- **Finishing layer:** It is a 20-30mm thick layer and faster to remove as there is no reinforcement in it. The same equipment is used to remove this layer too. It can either be removed or left on top of the floor slab.

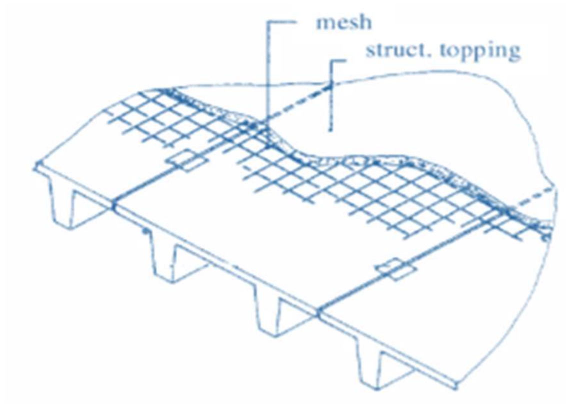


Figure 15: Concrete compression layer in double-T floor , source (Engstrom, 2008)

- **Break the connections**

Before breaking the connections, the elements are checked for pre-stressing. It is not a practice to check for post-tensioning in traditional demolition projects. It does not matter if the reinforcement is under tension or not as the entire floor is crushed down (Interview 02, 2020). However, it matters for when the building is deconstructed for component recovery. Prestressing can be achieved by pre-tensioning or post-tensioning. In pre-tensioning, the reinforcement is subject to tension forces before pouring the concrete whereas in case of post-tensioning it is done after the concrete has gained some strength. Pre- tensioning is not dangerous since the cables are bounded to concrete and can be cut along with concrete for deconstruction as in case of ordinary reinforced concrete. However, in post-tensioning, the cables are violently released as concrete is cut as it is not bonded and therefore needs to be planned well by an expert. In the case of prefab elements, the finishing layers are first removed to reach the connections then the concrete between the slabs is removed. The joints are located and concrete is removed from in-between the joints manually with hand wedge or compressor hammers. Two workers are needed for this job: one hacks the compressor and the other shovels and removes the debris away (Glias, 2013). Joints between the floor slabs, the slab and the walls, slabs and the columns are then sawed. To minimize the damage, a diamond saw is used. For cast-in-situ, the sizes in which the slabs are to be sawed are first marked following which, the elements are cut.

- **Lifting the slabs off the grid**

Most of the times the old connecting points are destroyed and new connections need to be made to lift the slabs. For instance, the new double T beams come with lifting eyes as shown in figure 16 but they get embedded in concrete once the finishing layer is poured over it. It is not possible to reuse these as lifting points anymore. Therefore, new connection points are to be made to lift the slab off the grid. There are different ways to lift the slabs such as drilling chemical anchors, drilling holes, using a crane with a fork, old lifting points, etc. The merits and demerits of each of these methods are summarized in table 2.

Figure 16:Lifting eyes of a prefabricated double- T beam, source (Levitt, 1990)

Table 2:Merits and demerits of lifting methods, source (Glias, 2013)

Lifting Method	Using Old lifting points	Using Crane with a fork	Drilling holes	Drilling chemical anchors
Cost	Cheapest method	Cheaper than drillings	less expensive than chemical anchors	Most Expensive
Time	Fastest if found usable	Faster than drilling	Time-consuming	Placed in 1 day, ready to use the other day
Disadvantage	-have to be detected and tested for quality - usually destroyed after first use and often found rusted	The wall beneath needs to be removed before for access. The fork cannot reach deeper into the building	It can damage the component	Most costly solution but slabs can be lifted from anywhere in the building

4.4.2. Material Handling Stage

Material handling is a crucial stage after the secondary elements have been lifted off the grid. There are various challenges when it comes to handling the secondary components on-site. For instance, the clearing of the site to ensure the unimpeded flow and stacking of materials, timely removal and drop-off, on-site removal of materials to minimize the loading, transporting and storage effort, providing sufficient room for processing such as de-nailing, stacking, ensuring that the reusable is not stolen from the site etc (Bradley, 2004). These challenges are systematically dealt with in the material handling stage. The processes involved in this stage are the modification, storage, transportation, repair and certification.

1. Modification

Modification refers to the changes that one needs to make to a demounted component before reusing it. It is especially the case when the elements are not designed to be reused or disassembled. Lesser modifications are needed in prefabricated elements as they have standard dimensions than in cast-in-situ slabs which are not designed to be deconstructed for reuse. There are various types of modifications that a component can be subjected to such as sawing to size, filling old cutouts holes which are not needed in the new design of the floor, removing fixings, drilling new connection points to lift the element and connect them again, remove nails and screws, etc (Bleuel, 2019). “No modification” means that the component is good to reuse without any changes. For instance, HCS can be reused without any modifications as the elements are standardized (Glias, 2013). As depicted in figure 17, one can opt for different combinations of modification depending on the requirements of new construction and the budget available for it. Naturally as the level of modification increases, the cost of modification increases as well.

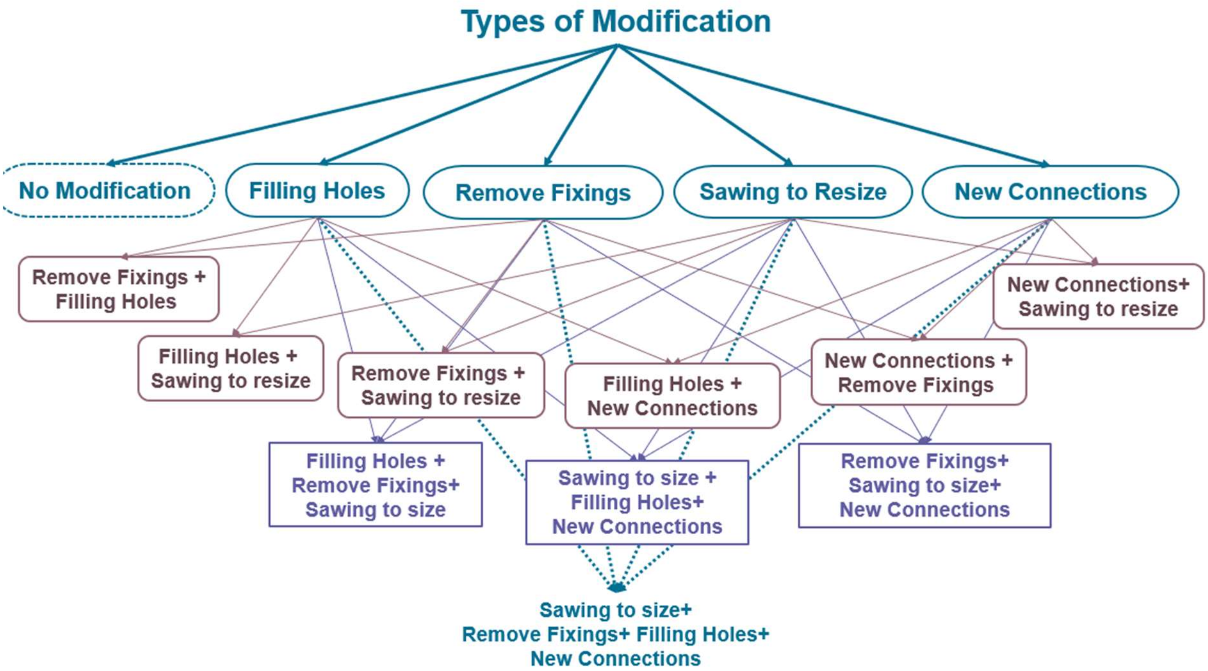


Figure 17: Types of Modifications. Self-illustration

The best way to modify is right after the removal of the component at the deconstruction site. However, it is possible only when there is already a buyer for the components and the delivery requirements are made explicit. For on-site modification, the site logistics are to be taken into account too, for instance, if there is enough space to modify the element and ensure their safe handling.

Insights from Interview:
Most of the contractors prefer to sell the components as they are. In case the requirements of the user are different then he has to modify it himself. This is because the demolition contractors lack the expertise and the budget to modify it.

2. Storage

The products once recovered from the building needs to be handled in a coordinated way to avoid unsorted pile-ups, blockages and double handling. In a traditional demolition, there is no cost of storage as the debris is mostly stored as a pile on-site until transported for treatment to the disposal plant. However, this is not the case for components deconstructed for reuse. They need to be stored at designated space ensuring minimum damage in handling. The type of storage solution affects not only the economic but also the environmental impact of the reuse process as explained in the following section.

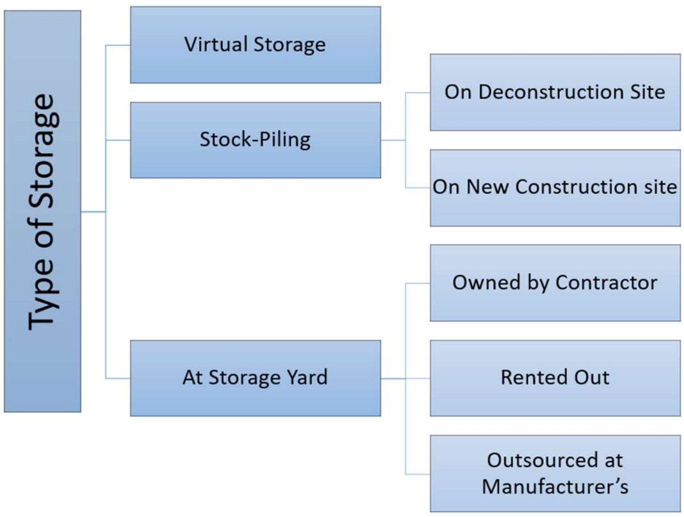


Figure 18:Types of Storage

Type of Storage: Salvage components can be stored at either the deconstruction site, the new construction site or at a designated storage yard as described below.

- **Virtual Storage:** In this situation, the building is assessed positive for deconstruction, the inventory is prepared but it is left intact to store the elements. This method of storage is chosen when there is no potential client to buy the elements beforehand. The building is then soft-stripped only on the inside, maintaining the envelope intact. It has many advantages like no storage cost, no transportation cost and emissions released in transporting the components to the storage yard, reduced modification costs and lesser damage to elements. The time while the building stands vacant is used to advertise the elements from the inventory to find buyers. However, this time implies additional operating costs on the owner such as energy, maintenance, administrative, etc. Estimation of the operating cost of an empty building is 24 euros/m2/ year (Glias, 2013). This cost can be compensated by renting the property meanwhile for other functions.

- **Stockpiling:** Stockpiling is done by stacking of components one over the other. However, before storing the elements they are labelled to ensure correct sequence of assembly for construction. Labelling further eliminates the chances of double handling and miscounting the components. It costs nothing but needs enough space on the site to stack. Stock-pilling can be done either or the deconstruction site or at the new construction site. Storage at the new building site maximizes the impact and efficiency of the reuse (Dijk et al., 2000). However, this is the case when there is already a site where these components can be reused. Often such solutions are adopted when it is difficult to store the elements at deconstruction site due to site restrictions such as limited space.

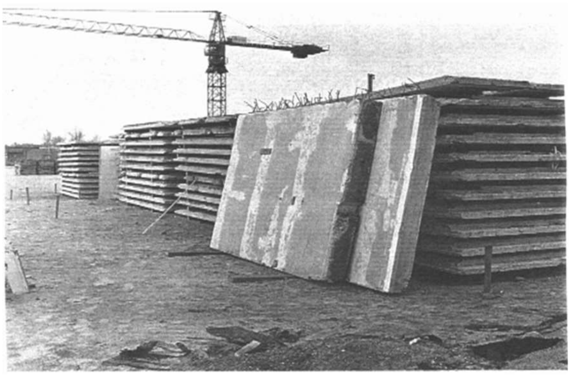


Figure 19: Stock piling at the construction site, source (Dijk et al., 2000)

- **At storage yard:** Floor slabs can be stored at a designated yard or warehouse when there is no immediate buyer of the components. It is not a preferable solution as the costs can be high in case the owner of the component does not own the yard himself and needs to pay rent for it. It is possible when the demolition contractor has a secondary product facility to store the product with other products at a self- owned yard. The firm does not incur extra costs in that case as other products are already stored at the location. However, it is very rare for a contractor to rent a space for storing secondary products without a buyer. It provides greater flexibility and freedom to the buyer/end-user than the owner of the components who needs to sell the components. Another option for off-site storage is at the company that produces the prefabricated concrete elements. They have space and hauling equipment (Glias, 2013). When stored at a storage yard, the elements can be sufficiently checked for quality. It also facilitates sale to multiple clients as they can buy the needed quantities and need not pay for all the components. However, it is a disadvantage for the owner of the components as he might be left with stock that no buyer wants to buy and he then has to bear the disposal cost of it. Storage at a yard also incurs additional transportation distances.

Alexandros Glias compared the two options of virtual storage and storage at a designated site and concluded than virtual storage is better than storage at a yard. However, a building needs to be deconstructed if the value of the building is depreciating as a result of structural vacancy since it implies high operating costs of the vacant structure whereas, in case of no depreciation, the building should be kept intact as it can be rented for revenue generation in case other is no buyer (Glias, 2013).

3. Transportation

The transportation of floor slab elements is both challenging as well as crucial in the reuse process. Transportation is needed when the deconstructed elements cannot be reused on the same site. In that case, they are either transported to the new construction site or a storage yard when they are stored for a given time and then transported to an end-user or treatment facility. Following three routes are possible for transporting the secondary components.

Figure 20: demolition site to storage facility, source: (Glias, 2013)

- On-site reuse, minimum transportation within 5km
- From the demolition site to the new project site
- From the demolition site to the storage facility to customer

4. Repair

In case of cracks or damage, the secondary components are to be repaired. The damage investigation begins with visual inspection during the audit. If spotted, specific tests are done to quantify the damage and thereby calculate the cost needed to repair it. For precast concrete, it is advised not to reuse elements with signs of localized corrosion, section loss, frost damage, etc. Further, avoid using pre-stressed slabs with corroded steel and wide cracks (Hradil et al., 2014). There can be damage by agents like fire, water ingress, etc. resulting in material deterioration as listed below (Bleuel, 2019)

- Spalling-off corners
- Honeycombs
- Entrapped air
- Scaling (by frost)
- Delamination surface
- Fire damage
- Discolouration of concrete
- Craquelé (small hairline cracks)
- Exposed reinforcement
- Moisture

The two most common types of repair are painting the surface to protect the exposed reinforcement against degradation and applying a coating of grout/mortar. Other solutions include an epoxy coating or polyurethane coating to protect the floor against wear and tear.
Any repairs if needed, for instance, are done either on-site or at the new project site which is not favourable due to space restrictions or at the storage place.

Insights from interviews:

In the interviews, it was found that repair of recovered components is not a common practice. The components are sold the way they are recovered. Hence, the elements which suffer some kind of degradation are often demolished instead of being repaired for reuse. It results in lesser recovery of secondary products for reuse. Repair is often a costlier affair, poorer the physical condition of the element higher is the repair cost. Therefore, none of the contractors wants to do repair works. They instead look for buyers who want the products as they are. Repair if needed is done by the end-user himself (Interview 02, 2020), (Interview 03, 2020), (Interview

05, 2020), (Interview 06, 2020), (Interview 07, 2020), (Interview 08, 2020). The buyers are from their business network, if one buyer has specific repair requirements and he cannot test the elements himself, the elements are then sold to other buyers or send for recycling (Interview 03, 2020). “By repairing and refurbishing it, you go to a lower R in the 7R model, we want to achieve the highest R and therefore sell it the way we recover it” (Interview 05, 2020). “Repair means putting more money into it which diminishes the profit we make by selling it” (Interview 06, 2020).

5. Certification

Certification is defined as a third-party attestation of the products, i.e, a third-party issue a decision stating that the product fulfils the specified requirements (ISO, 2004). Furthermore, the third party must be an assessment body with the accreditation of its competence to certify the product by another independent body. A product is certified to ensure that it fulfils not only the performance test but also meets the qualification criteria stipulated by standardized directives and regulations.

Deconstructed components lose their legal validation and need to be certified again. Builders get the product at a good price but are willing to reuse the components only when the quality can be assured (Eurostat & Deloitte, 2015). Certification of structural component for reuse is more crucial than for non-structural component. The client wants to use certified products as it serves as a guarantee against failure and also dictates the party responsible if and when the failure occurs. As per the Dutch building codes, only the materials that have been certified can be used in the building industry. It causes problems with old reused materials as they need to get certification before they can be reused (Dorsthorst & Kowalczyk, 2005). There are different certification schemes which describe the process to test a new product and obtain certification for it. However, there is no specified system to certify salvage materials and components as a result of which the risks associated with their reuse is high (Gorgolewski, 2017).

Is Performance testing same as certification?

Performance testing is often used synonymously to certification. However, they are different. Performance testing refers to the process of testing to determine one or more characteristics of a product according to a prescribed procedure. It is a declaration i.e. an attestation made by the first party itself (ISO, 2004) whereas certification must be a third- party assessment. The requirements for performance testing are straight forward when compared to certification as listed below(Gorgolewski, 2017).

- The products should not contain any prohibited/hazardous compounds
- The products are not exposed to pollution and do not show signs of degradation
- The products are technically sound for reuse, properties of the products are not affected by previous use
- The products have not been harmed due to deconstruction

Following are the certification scheme requirements for re-use of salvaged products (Gorgolewski, 2017)

- Define the application of the product concerning existing standards
- Define the origin of the product i,e, information on the historical background
- Provide guidance for deconstruction to ensure process control
- Guidance for visual inspection before deconstruction
- Have quality control program in place
- Develop a system for approval/rejection of products
- Define the qualification of the persons involved in performance testing
- Dictate the requirements for the level of acceptable impurities
- Have a documentation system in place
- Ensure training of staff

CE Marking: a solution for salvage products?

CE making is used to certify new construction products to ensure compliance with specifications as per the Construction Product Regulation (CPR). However, it is limited to only new products, the existing CE marking procedures do not cover the subject of salvaged products. It is not clear how CE marking can be adopted for salvaged components in Europe. The process involves sampling tests and factory production controls whereas in case of salvage product there is little information available on the factory front as it is very challenging to find the manufacturer's details and the processes adopted in the production of the component in case of old buildings but what is crucial is to take into account the historical data of the product use which may have affected its quality (Gorgolewski, 2017). It is therefore argued that the salvage products and reclaimed building materials be exempted from CE marking obligation (Hradil et al., 2014). Hence, CE marking does not seem to be the right way of certifying the secondary components.

Current practice (insights from the questionnaire)

In the existing scenario, certification is not mandatory. The seller/contractor needs to prove that the slabs fulfil the requirements. The certification can be used as a tool for this.
There is no certification scheme for secondary concrete components or other materials, there is a certification scheme only for the granulates. Since there is a lack of standard directives and regulations to certify secondary building components, the common practice is to develop a generic scheme and carry out product-specific tests to determine the performance of the product. However, no standardized certificate is provided as there are no directives and regulations for salvaged products making the certificates issued by third parties questionable. Every third-party has its own compliance procedures which limit the credibility of the certification.

Certification is a costlier process than performance testing as it requires accreditation of the laboratory. The cost depends on the number of audits conducted and the level of testing performed. Components are often certified on an annual basis and sometimes on an m^2 basis. Low-level certification without accreditation and according to a simple scheme can cost about 1500 euros to 2500 euros per year; a medium level of certification is the one with accreditation, few tests and limited audits costing about 2500-5000 euros a year whereas high-level certification involves several tests and audits costing about 5000-15000 euros annually.

4.4.3. Consumption of secondary component

The components retrieved from deconstruction have an economic value called the salvage value. It is the cost-benefit obtained by either selling the recovered component in the market or reusing it in place of a new component. Higher the salvage value of the secondary product, lesser is the deconstruction costs. Generally, if the recovery cost is high and the salvage value of the product is low, deconstruction turns uneconomic (Bradley, 2001). The gross deconstruction costs are generally higher than demolition but the salvage cost can substantially reduce the net deconstruction cost and make reuse a profitable case by generating revenue from the sale of secondary components. Several studies have proved that taking into account the salvage costs, the deconstruction cost turns out to be lower than demolition. For instance, Brandley Guy found that the deconstruction cost is 37% lower than demolition when salvage is taken into account, Amol Tatiya in his research observed deconstruction cost to be 30-50% lower with salvage revenue, etc. Different products have different salvage value depending upon their quality and condition. Consumer perception and the lack of information also affects the salvage value (Icibaci, 2019), (Coelho & De brito, 2013). Guy Bradley estimated the salvage cost as a percentage of the retail price from local building materials suppliers as shown in table 3 (Bradley, 2004).

Table 3: Salvage Value of secondary components, source (Bradley, 2004)

Material type	Price range as % of retail price	Description
Low value	10 - 25	Materials whose value is a small fraction of new materials. The low value is a function of their condition or original value.
Good quality	50 - 85	Materials whose value is a significant portion of new materials. These materials can substitute one-for-one with readily available new materials. The previous use does not affect the way they can be reused.
High value	100+	Materials whose value may equal or exceed that of new materials. The value of these materials has increased over time because of scarcity, similar qualities currently expensive to acquire and their reprocessing adds value.

Insights from interviews

Findings from the interviews suggest that the salvage value varies from 20%- 50% of the price of the new component. It is mostly never more than 50% but there is a growing interest for secondary components so one can expect this scenario to change. In some cases, you can even sell it at the price of a new component but that is very rare. Young enthusiasts do not mind paying the same price for secondary components as a new component to support circularity.

Salvage value depends on the material type, the quality of components and the situation of the market. If there is more demand, then the salvage increases. If the material is good quality then people are willing to pay higher. It was also mentioned that the contractors prefer to recover the good quality components for which they can estimate the worth in advance.

Type of consumption: The components recovered by deconstruction are to be reused profitably. These components can either be consumed by the owner himself, the deconstruction contractor or can be sold to a third party. Following are the possible consumption streams for the secondary components:

- **Consumption by the owner:** when the building owner hires the deconstruction contractor and retains the ownership of the building materials recovered. It is often the situation when the owner has a reuse plan for the recovered components on-site or at another construction site. In this case, a lot of costs is saved as it limits the number of actors involved in the reuse process. For instance, the extra time deployed in demolition can be compensated by the time savings in purchasing new products (Michael, 2018), storage cost is saved and there is often lesser or no transportation involved.
- **Consumption by the Contractor:** Owner sells the materials within the building to the contractor. The worth or the salvage value of the components are discounted from the contract fee. This is the most common type of contract found in practice.
- **Sell to the third party:** Finding the end-user is a big challenge and determinant of reuse feasibility (Bradley, 2001). It can be done in the following ways
    - **Sell to business-network**: The contractor often arranges for the sale of the components within his network of buyers and connections in the secondary product's market. It consumes a lot of time and has significant costs (Bradley, 2001).
    - **Using a broker**: an individual or a firm dealing with secondary products, having a business network.

- **Selling on the internet**: advertisements through the internet can reach to the national customer base, however useful only for high-value products as the shipping costs are high for long distances (Bradley, 2001).
- **Put on auction**: it can be a site auction or regional auction. Site auctions are promoted on media through newspapers, radio, online mediums. On the given day, products are displayed and people submit bids. On-site sales (at the deconstruction site) considerably reduce off-site materials handling costs and increases the salvage revenues (Bradley, 2004). However, site clearance, material handling and time scheduling get challenging when products are stacked on-site for sale. Another way to find potential buyers is to participate in regional/periodic auctions. These are the common auctions in the area held periodically. However, one needs to store the elements until the auction. Such auctions are more common for the products of soft-stripping but not so much for structural floor elements.

- **Donate to society:** The owner can donate the materials to charity if he cannot find a reuse for it himself (Bradley, 2001). Although the owner of components does not get paid the monetary returns in terms of sale of the components, he can avail tax benefits from the government. A non-profit organization performs deconstruction, charging only direct labour costs and the owner donates the materials as tax write-offs to the organization. Such contracts are not popular in practice.
- **Manufacturer takeback:** Here the ownership of the product remains with the manufacturer of the product who claims it back after EOL. It is based on a lease agreement. However, this approach is futuristic and not found in practice.

5

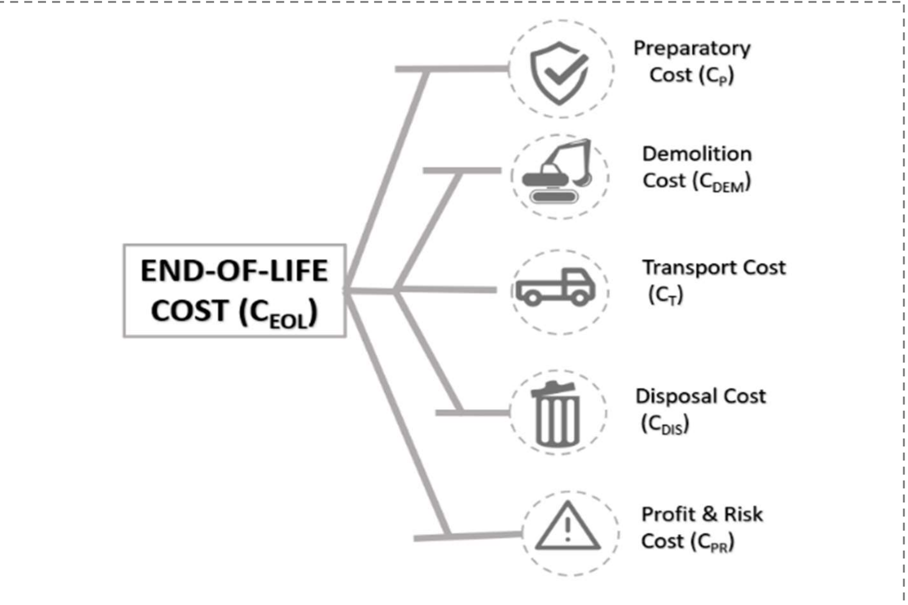
REUSE COST ANALYSIS

Cost is an important factor. Often the decision to deconstruct for reuse or demolish is based on the cost. This chapter explains the various costs involved in the process of reuse. First, the cost of EOL treatment is elaborated to understand which EOL costs are involved in a traditional demolition project. Thereafter the cost of reuse is derived using the process-driven approach. Furthermore, the feasibility condition under which reuse is economic is explained following which the concept of tipping points is explained. This chapter answers the following research sub-questions:

Q4. What are the costs involved in the reuse of structural floor elements?
Q5. What is the feasibility condition? What are the tipping points for an economically feasible reuse case?
Q6. What are the reuse scenarios?

5.1. EOL Treatment Cost (C_{EOL})

C_{EOL} costs are the costs incurred in a traditional demolition process. It consists of the cost of planning (C_P), demolition cost (C_{DEM}), transportation costs (C_T), disposal costs (C_{DIS}) and the profit and risks costs (C_{PR}) involved in demolition as shown in figure 21.



$$C_{EOL} = C_P + C_{DEM} + C_T + C_{DIS} + C_{PR}$$

Figure 21: End-of-life Cost, self-illustration

There are various factors which affect the demolition costs such as the height of the building, location, materials used, presence of hazardous method, etc (Dijk et al., 2000), (Tatiya, 2016). Alexandros Glias investigated the demolition cost for a 6 story high office building built in 1988 with precast concrete slabs. His findings as shown in figure 22, suggest that equipment and workers comprise about 60% of the total demolition cost, followed by transportation cost of debris, project costs or the site preparation cost, general costs which are the permit costs and other unsaid costs, profit and risks costs and the various costs (cost of the ramp to facilitate the movement of heavy machinery) (Glias, 2013).

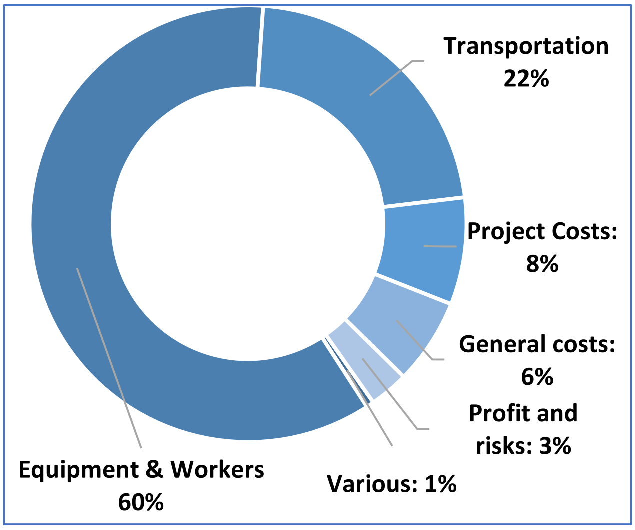


Figure 22: Costs Incurred during demolition, Source: (Glias, 2013).

C_{EOL} Calculation: The **C_{EOL}** cost is calculated based on the findings of the interviews where the demolition contractors shared their practices of treating the debris. For calculation, it is assumed that the debris is separated on-site and mixed waste is sent to waste collector (most-common practice). The scrap revenue is not accounted here since it is taken care of by the waste collector. Hence, the calculation is based on the following assumption:

- 90% of the total debris goes for reuse in the road industry. It generates revenue of 4.5 euros/ton of debris. The delivery point is assumed to be at a distance of 50km.
- 10% of the debris is mixed waste which is sent to a waste collector who charges 90 euros/ton of debris (Icibaci, 2019). The collector is assumed to be located within a 20km radius.

$\boldsymbol{C_{EOL}}$ is given by the following equation:

$$\boldsymbol{C_{EOL} = C_P + C_{DEM} + C_T + C_{DIS} + C_{PR}} \quad \textbf{...................Eqn A}$$

Where,
C_P= Preparatory Cost
C_{DEM}= Cost of Demolition
C_T = Cost of Transportation
C_{DIS} = Cost of disposal
C_{PR} = Profit and risk cost

- **Preparatory (C_P):** It can be broadly divided into planning and site preparation costs.

The preparatory cost amounts to about 15% of the total EOL cost. It costs about another 18% of demolition costs if hazardous materials are present (Bradley, 2004).

Preparatory (C_P)= Site preparation Cost + Planning Cost

- **Site Preparation:** The site preparation refers to setting up the site before starting to demolish. It is same as preparing the site for deconstruction which involves installing the site hut, toilets, safety lines and safety nets.
- **Planning:** involves obtaining the permit, audit, making waste management plans. It varies with the size of the project. For instance, a big project that takes 6 months to demolish requires about a week into planning whereas for a project that lasts 6 weeks, it requires a day or two into planning (Interview 02, 2020). In this case, the investment

of 2 days for a 6 weeks project is about 7 % of the total demolition time, whereas 7 days for a 6 months project is roughly 4% of the total demolition time. So for small projects, percentage-wise, the preparatory costs are higher than for big projects. Assuming a demolition rate of 300 m2/day, the following planning costs apply to different projects

Table 4: Planning cost per type of project, source: Interview 02

Type of project	Demolition Time	Area (m^2)	Planning Cost (%)
Small- Medium sized	3-10 weeks	4500-15,000	7
Large sized	>10 weeks	>15,000	4

- **Demolition (C_{Dem}):** It is the cost of breaking the structure. It is calculated by the number of labour hours and the machinery used on-site to bring down the structure. The total cost varies depending on the size of the building or the total GFA. For a small scale object, the demolition cost is estimated to be about 31- 38 euros/ m^2 whereas for high-rise buildings it is 36 -48 euros/ m^2 (Arcadis, 2017).

Insight from Interviews: A 60-ton crane is used to demolish the building by one labour worker operating the crane. Assuming a demolition rate of 300 m2/day, the total number of days required to demolish the building is calculated. It is for these days that the labour is hired and the machinery is rented out.

Demolition (C_{Dem})= Labour Cost+ Machinery Cost

- **Cost of Transportation (C_T):** The cost of transporting the debris depends on the quantity of debris which in turn determines the number of trucks needed to carry the debris; the unit price of transportation in euro/truck/ton and the distance to which the debris is to be transported. Following are the two transportation routes opted for calculation:
  - 90% of the total debris is transported over a 50 km distance to be delivered to road industry.
  - 10% of debris i.e. mixed waste is transported over 20km to be delivered to a regional waste collector.

- **Cost of disposal (C_{Dis})**: The cost of disposing the debris depends on the quantity of debris generated and the unit price of treating this debris. In case the debris is sent to waste collector, the demolition contractor needs to pay for this service whereas if the debris is sent for reuse in the road industry for sub-base and foundation, the contractor earns revenue out of it. Based on the findings of the interview, the following practices are assumed for calculating the disposal cost:
  - 90% of the total debris is sent to the road industry generating revenue at 4.5 euros/ton of debris
  - 10% of debris i.e. mixed waste is sent to waste collector who charges 90 euros/ton of debris.

- **Profit and Risk Cost (C_{PR}):** The profit and risk costs for demolition is taken to be 3% of the total demolition costs as it is a well- known process and uncertainties are minimum (Glias, 2013).

5.2. Cost of Reuse

There are various direct and external costs involved in the reuse of building components. For example, the deconstruction cost, transportation, storage and reconditioning, tipping fees, fines on mixed materials and cost of secondary and virgin materials(Liu & Wang, 2014). It is important to understand these costs and their dependencies to optimize the net cost of reuse. The most significant cost determinants as identified by Polina Michael in her book are the labour costs (higher for deconstruction than demolition) and extra time followed by inventory cost, transport and storage, the existence of market and network of businesses. From within the structural components, findings of Alexandros Glias suggest that deconstruction of floor slabs (HCS) costs more than other structural elements. It was found to be as high as 42% of the total deconstruction cost with another 14% of the cost incurred in removing the concrete topping. Other elements such as the beams, columns and walls incurred 8%, 9% and 15% of the deconstruction costs respectively as shown in figure 23.There are various

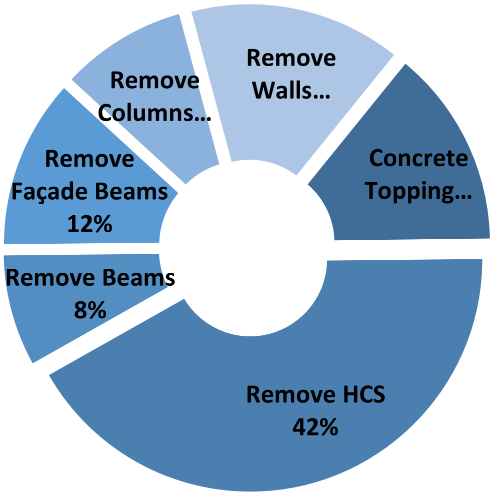


Figure 24: Deconstruction cost of floors vs other components, source (Glias, 2013)

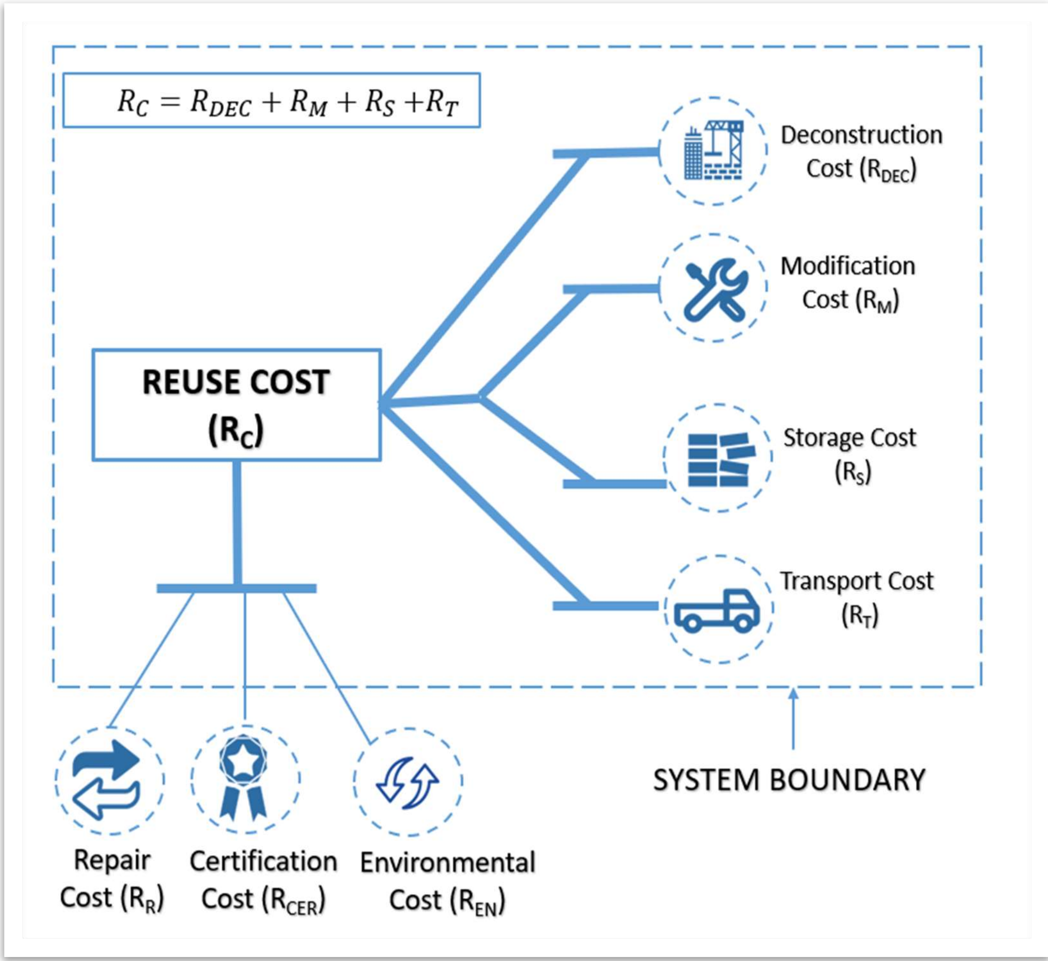


Figure 23: Reuse Cost System Boundary, Self-illustration

costs involved in the reuse of building components (figure 24) such as deconstruction costs, modification costs, storage and transportation costs, environmental costs, cost of rebuilding with secondary components, repair costs, certification costs, etc. However, not all these costs components are equally significant. For instance, it can be argued if to include environmental costs in the feasibility calculation since these are virtual costs required to be declared but not yet paid by the polluter. Furthermore, other costs like the rebuilding costs can be omitted as they are more or less same as the building costs with new components. It is therefore important to specify which costs are used as contributing costs for calculating the reuse feasibility and clearly define the reuse boundaries.

Reuse Cost Boundary Condition
Figure 24, shows the system boundary for the reuse cost calculation. It includes the deconstruction costs, the modification costs, the storage and transportation costs. This boundary condition is established based on the insights of the interviews. It includes all the processes which are a part of the current practice of component reuse. Other costs elements such as the environmental costs, the repair and certification costs are not included in the boundary condition as these costs are not an active part of the current reuse practice as learned from the interviews. However, one cannot neglect these costs. In an idealistic situation, the demolition contractor must repair the elements, certify them for quality and take into account the environmental savings he is making. Therefore the effect of these costs elements is separately studied, i,e, futuristic scenarios are generated to study what if these costs are included in the reuse process.

$$\boldsymbol{R_C} = (\boldsymbol{R_{DEC}}) + \boldsymbol{R_M} + \boldsymbol{R_S} + \boldsymbol{R_T} \quad \text{..............................} \textbf{Eqn 1}$$

5.2.1. Deconstruction Cost, (R_{DEC})

Calculation of deconstruction costs is not a known procedure (Glias, 2013). It depends on several factors such as the location, type of building, construction method, age of the building, type of connections, number of different components, tools and techniques used, etc.,(Dijk et al., 2000), (Philip, 2001), (Tatiya, 2016), (Michael, 2018). To thoroughly investigate the deconstruction costs in greater depth, a process-driven approach is adopted. The process of deconstruction as elaborated previously is mapped with the associated costs that are incurred during each sub-process. Following are the constituent cost components of deconstruction cost

1. Preparatory Costs (R_P)
2. Disassembly Costs (R_D)
3. Profit and Risk Cost (R_{PR})
4. Salvation Cost (R_{SAL})

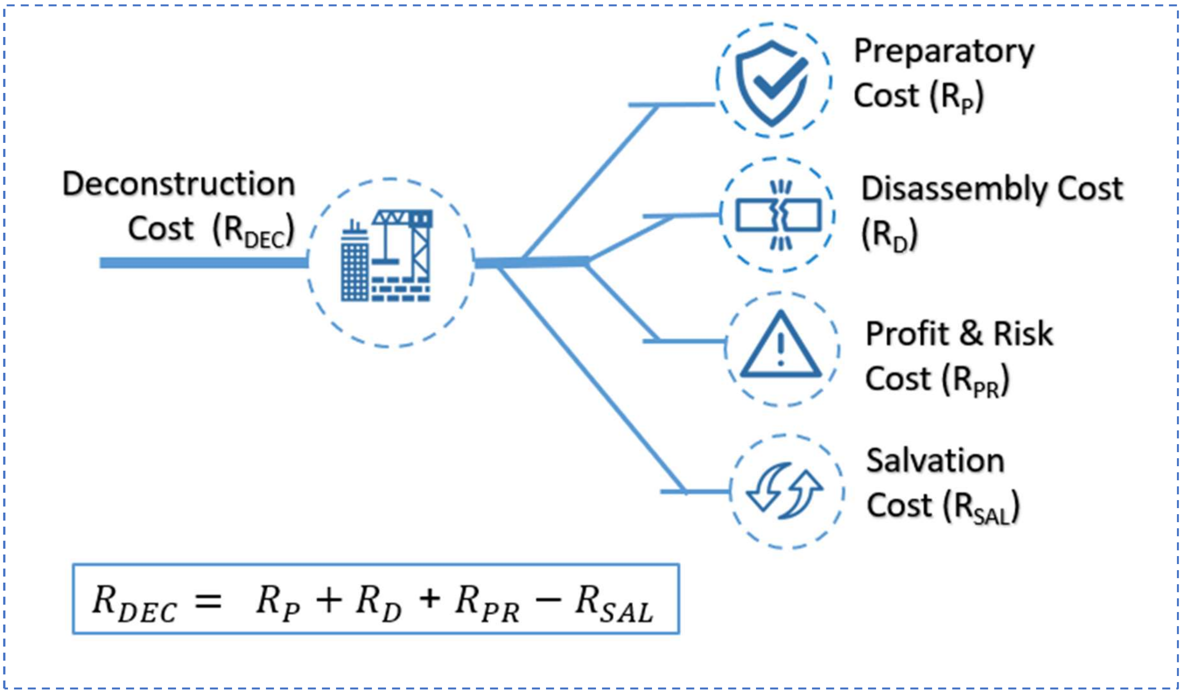


Figure 25: Deconstruction Cost Components, Self-illustration

The deconstruction cost (R_{DEC}) is given by equation 2.1 or equivalently by equation 2.2
The sum of preparatory cost, disassembly cost and profit and risk cost is termed as gross deconstruction cost ($R_{DEC,G}$). It is the cost of labour and machinery that goes into deconstruction and is higher than traditional demolition. Deconstruction cost (R_{DEC}) is derived by from ($R_{DEC,G}$) by taking into account the revenue generated by selling the salvaged products referred to as salvage cost (R_{SAL}) which is explained later in detail.

$R_{DEC} = R_P + R_D + R_{PR} - R_{SAL}$ ……………………..Eqn 2.1

$R_{DEC} = R_{DEC,G} - R_{SAL}$ ……………………..Eqn 2.2

Where,
$R_{DEC,G} = R_P + R_D + R_{PR}$
$R_{DEC,G}$= Gross Deconstruction Cost
R_P = Preparatory Cost
R_D= Disassembly Cost
R_{PR}= Profit and Risk Cost
R_{SAL} = Salvage cost
The following section discusses each of the deconstruction costs components in detail:

1. Preparatory Cost (R_P)
The cost of preparing a building for deconstruction is called “Preparatory cost”. It can be broadly divided into planning and site preparation costs. The details of preparatory cost calculations can be found in appendix 3.

Preparatory (R_P)= Site preparation Cost + Planning Cost

- **Site Preparation Cost:** It is the cost of installing the site hut, toilets, safety lines and safety nets. These costs are also common for both deconstruction and demolition. The total site preparation costs are found to be 8% of the deconstruction cost (Glias, 2013).
- **Planning Cost:** involves obtaining the permit, audit and making waste management plans. The planning effort in deconstruction is certainly higher than that in demolition. For deconstruction, planning cost is assumed to be 6%-8% higher than in demolition depending on the size of the project. This assumption has been verified with all the interviewees during interviews to align the assumption with experience from the ground. Hence, for a small to the medium-sized project, the planning cost for deconstruction is assumed to be 15% (7% in demolition project) of the gross deconstruction cost whereas for a large-sized project it is assumed to be 10% (4% in demolition project).
- **Detoxification Cost:** This cost is incurred when hazardous materials such as asbestos, lead paint, etc are present. The costs vary from 9 euros/m2 to 39 euros/m2 depending on the quantities of the material present (Arcadis, 2017). When identified in the survey, the asbestos removal costs are found to be 15% of the total demolition costs(Bradley, 2004), (Tatiya, 2016). However, since the asbestos survey and remediation costs are the same for both demolition a deconstruction (Bradley, 2004), these costs are not considered for cost comparisons.

2. Disassembly Costs (R_D)

The cost incurred during the execution/disassembly process is termed as disassembly cost. In simple words, it is the cost of labour hired and the machinery rented to carry out the disassembly. However, this labour and machinery is used in performing different tasks to disassembly the floor slabs for reuse. There are five such tasks as listed below:

- **Building the support system:** Supports are needed before cutting the elements to ensure safety against system failure and unexpected collapse. The cost of building these supports is estimated at one €/m2 (Bleuel, 2019).
- **Removing concrete topping:** it depends on the type of concrete topping. Compression layer of 50mm thickness can be removed at 150m2/day whereas, for a 30mm thick finishing layer, it is at 200m2/day (Glias, 2013). The job is done by two workers with a pneumatic hammer.
- **Removing concrete between the slabs:** After breaking the concrete topping, the concrete between the longitudinal joints needs to be removed. It is estimated to cost 2 €/m (Bleuel, 2019).
- **Breaking the connections:** the connections are saw with a diamond saw across the longitudinal direction to disconnect the slabs from each other. It is estimated to cost 35 €/m (Bleuel, 2019).
- **Lifting the slabs**: Lifting job is carried out by two labour workers, one worker connects the chains and fork while the other coordinates on the ground for placing and stacking them correctly. A 100-ton crane is used for this purpose. The execution rate is about 0.25hr/slab i.e. it takes about 15 mins to lift a slab (5 for connecting chains, 5 for lifting and landing, 5 disconnecting and getting to another slab) (Glias, 2013).

Hence,

Disassembly Costs (R_D) = Cost of building support system+ Cost of removing concrete topping+ Cost of removing concrete between the slabs+ Cost of breaking the connections+ Cost of lifting the slabs

3. Profit and Risk Cost (R_{PR})

It includes the profit, uncertainty and the risks involved in the process. Since the deconstruction for structural component reuse is fairly new, there can be an unforeseen hike in costs such as execution delays leading to higher labour and machinery costs, failure to find a buyer, etc. These risks can be better assessed in a demolition process than in deconstruction as the latter is a known practice. For deconstruction, the profit and risk cost is assumed to be 10% for calculation purposes (Glias, 2013).

4. Salvation Cost (R_{SAL})

The salvage value varies for different components depending on their demand, quality, price of the original product, etc. However, one thing is certain that the salvage value is almost always lesser than the price of the original component. For products with no information on performance, they are sold generally at 50% of the price of a new product which is the wholesale price of the secondary product (Bradley, 2004), (da Rocha & Sattler, 2009), (Glias, 2013). For calculation, the salvage cost is assumed to be 40% of the retail cost of the new component.

5.2.2. Modification Cost (R_M)

The costs incurred during the process of modifying the element for reuse are termed as modification costs which vary depending on the type of element i.e, beams, columns, floor slab, etc and also on the type of modification method adopted. For prefabricated HCS, modification cost is estimated at 37 euros per element which includes sawing once to adjust the sides, creating new openings and filling the old holes (Glias, 2013). This modification is more or less the most common modification a floor element is subjected to. However, it is

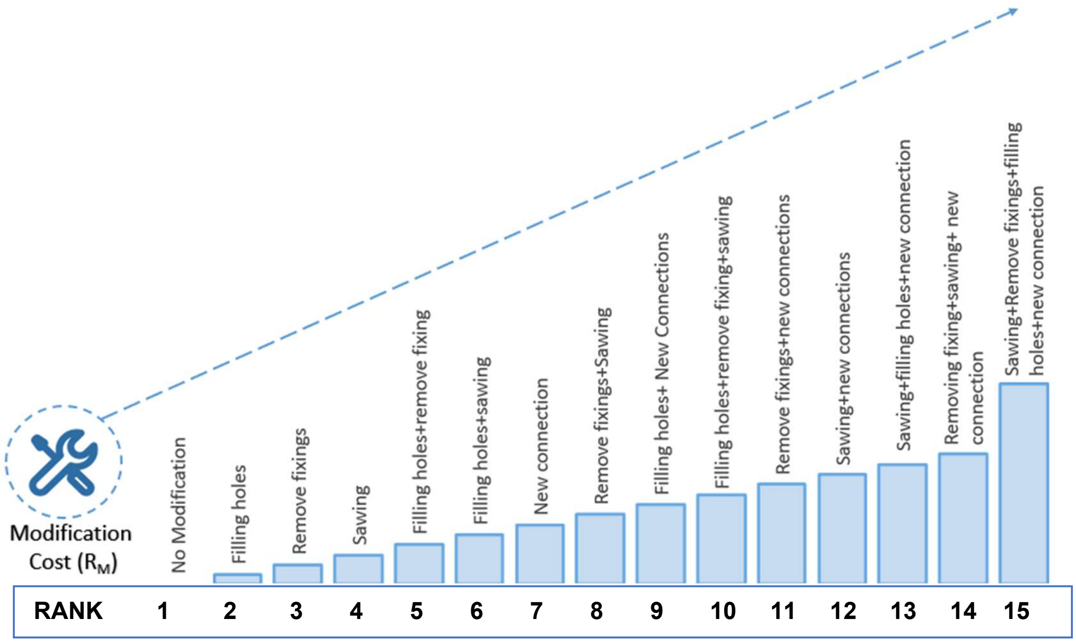


Figure 26: Rank of Modification per type, self-illustration

possible to have no modification needed for floor slabs at all. There are different types of modifications that an element can be subjected to as depicted in figure 26. Each type of modification is assigned a rank based on the cost needed to apply that modification. This is done to easily refer back to modification types. One can observe that the rank increases as the cost of modification increases. The lowest (rank 1) is the "no modification" where no treatment is given to the slab whereas the highest modification cost (rank 15) is incurred when the slabs are subjected to "sawing+ remove fixings+ filling holes+ new connections". Depending on the budget and the requirement of the user, the appropriate modification type can be adopted. In the idealistic situation, one would want enough budget to opt for the highest modification possible. The per-unit prices and the calculation method for modification cost are elaborated in Appendix 3.

5.2.3. Storage Cost (R_S)

As discussed earlier in chapter 4, the secondary components can either be stored on-site by stockpiling, virtually stored onsite or stored for a given time in a storage yard. There is no cost incurred in stock-piling at the deconstruction or the construction site, however, site logistics needs to be maintained well for it. It is beneficial for big demolition sites like airports, housing blocks, etc where materials can only be stocked for 1 year before disposal and 3 years before recycling (Commission European, 2016). For virtual storage, the operational costs of an empty building are assumed to be 24 euros/m2/ year (Glias, 2013). The cost of storing the components at the storage yard is 12 euros/m2/ year (Bleuel, 2019). For yard storage, way of stacking plays a role in determining the total cost of storage as it governs the total m^2. HCS are stored in stacks of 10 (Icibaci, 2019). For calculation, all types of floor elements are assumed to be stored in the stack of 10.

5.2.4. Transportation Cost (R_T)

Transportation over long distances is neither economically nor environmentally attractive. Over a distance of 35 km, the building materials cannot be transported by road and need rail or ship transportation (Commission European, 2016). The transportation cost depends on the route of transportation and the number of kilometres covered as discussed below:

- **No transportation cost**: in case of on-site reuse
- **From the demolition site to the new project site:** The new project site is assumed to be within a distance of 50kms from the deconstruction site.
- **From the demolition site to the storage facility to customer**: the storage site is assumed to be within the radius of 30km. The maximum distance from the storage site to the end-user is another 30km (Glias, 2013). However, the local market radius is around 120km (Bradley, 2001). Therefore, the maximum total distance, in this case, is taken to be 60-150km.

Putting values from Eqn 2.1 into Eqn 1, the result equation for Reuse Cost

$$\boldsymbol{R_C = (R_P + R_D + R_{PR} - R_{SAL}) + R_M + R_S + R_T} \quad \text{......................Eqn B}$$

Type of Reuse Cost Components: There are two types of costs: variable costs and fixed costs. The fixed cost components remain constant for a given project as these cost components are process-oriented. For instance, the end-of-life cost (C_{EOL}) is a fixed cost as all the constituent components of it are fixed for a given project: the demolition cost can be deterministically obtained as the sum of labour and machinery cost needed to carry the activity; the transportation distance is fixed to 50km and the disposal cost is determined based on the established treatment methods. Hence for a given project, C_{EOL} does not change. However, there are other types of costs called the variable costs. These are choice-based components which can be set by the owner/demolition contractor. There exists a range of choices from which one can choose. The fixed costs cannot be controlled by the user but the variable costs are controllable. For instance, in the case of R_C, the transportation distance, the decision on storage duration, the level of modification in the

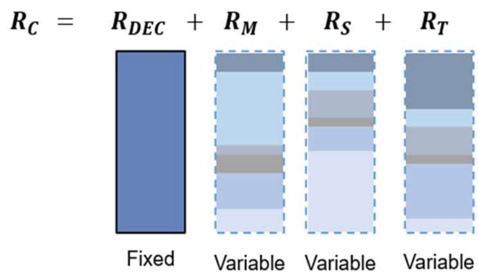


Figure 27: Type of Reuse Cost Components

component, etc can be decided by the contractor. The type of each reuse cost component is presented in figure 27.

- **Deconstruction Cost (R_{Dec})**: Fixed

Depending on the size of the project, the deconstruction cost can be deterministically obtained as the sum of labour and machinery cost needed to carry the activity.

- **Modification Cost (R_M):** Variable

The level of modification needed varies depending on the requirements of the end-user. He might ask for sawing to sizes and other modification like de-nailing, filling holes, etc. or he can buy the elements as it is.

- **Storage Costs (Rs):** Variable

It varies depending on the type of storage and the duration for which the elements are stored.

- **Transportation Costs (R_T)**: Variable

The elements can be reused at the same location or be transported over different distance depending on the buyer's location.

5.3. Feasibility Condition

To decide if to reuse or demolition a building, the economic feasibility needs to be assessed. The feasibility condition states that reuse of components is viable only when the total cost of reuse (R_C) is lesser than or at max equal to the cost it incurs to demolition building i,e, C_{EOL}. For cases when R_C is greater than C_{EOL}, demolition is preferred over deconstruction as extra costs are incurred in deconstruction.

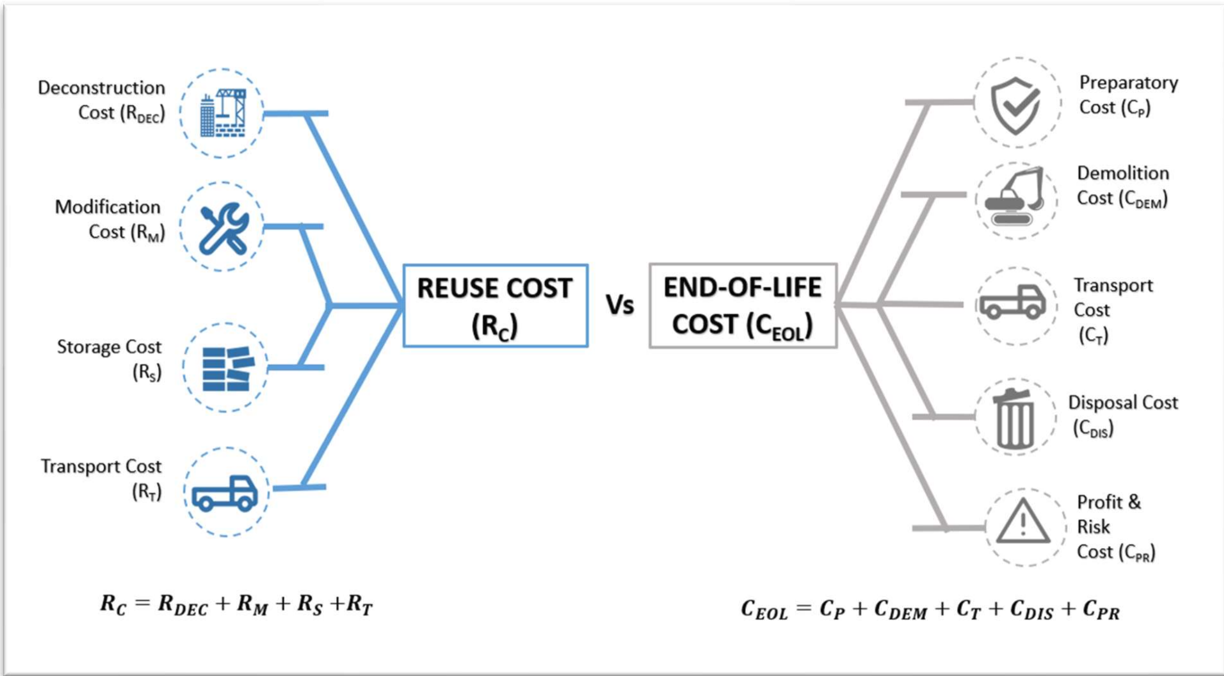


Figure 28: Cost of reuse vs end-of-life cost, self-illustration

$$Cost\ of\ Reuse\ (\boldsymbol{R_C}) \leq End-of-life\ \ Cost(\boldsymbol{C_{EOL}})\ldots\ldots\ldots$$ Feasibility Condition

Putting values from Eqn A and B into feasibility equation

$$\boldsymbol{R_{DEC} + R_M + R_S + R_T \leq C_P + C_{DEM} + C_T + C_{DIS} + C_{PR}}$$ **.....Eqn C**

Tipping Points

Tipping points are defined as the highest values of variable cost components beyond which reuse of the given component turns uneconomical. It represents the maximum budget that can be spent on a variable cost while keeping the total reuse cost lesser than EOL cost. For instance, the highest transportation distance for which a component can be transported; the highest rank of modification that can be applied on the secondary product; the highest virtual/yard storage that is economically feasible for a component. It is important to note here that the tipping point is not the same as the most optimum value of Rc. Tipping is defined for one variable cost component and as this given cost component say transportation distance has reached the tipping point; the value of other variable costs such as the modification or the storage is called as "corresponding boundaries". For example, if the tipping point of transportation is 4km, the type of modification that can be applied to the component after transporting them to 4km is termed as "corresponding modification". Say the corresponding modification at 4km is "filling holes". However, one can expect that the tipping point for modification (maximum possible modification) will be higher than its corresponding value and equivalently the corresponding transportation will be lower than the transportation tipping point. An inverse relation is observed between the tipping points and the corresponding boundaries.

5.4. Reuse Scenarios

Three different reuse scenarios are developed to analyze the reuse cost components in greater depth. These scenarios focus on the variable costs components of the reuse cost and their interaction with the fixed components.

5.4.1. RS1: Direct Onsite Reuse

It is presumably the most efficient scenarios of component reuse where the recovered products are reused on the same site, i.e, no storage and no transportation cost. The highest cost savings are observed in case of on-site reuse of components rather than using on another site (Glias, 2013).

System Boundary_ RS1: As mentioned earlier, reuse scenarios are developed to study the impact of variable cost components (R_M, R_S and R_T) as they interact with the fixed cost component (R_{DEC}). The system boundary explicitly states what value of each of the variable cost lies within the given scenario. For RS1, the system boundary is shown in figure 29.

- The deconstruction cost is fixed
- **Modification Type**: all types of modifications and combinations of modifications are included within the system boundary.

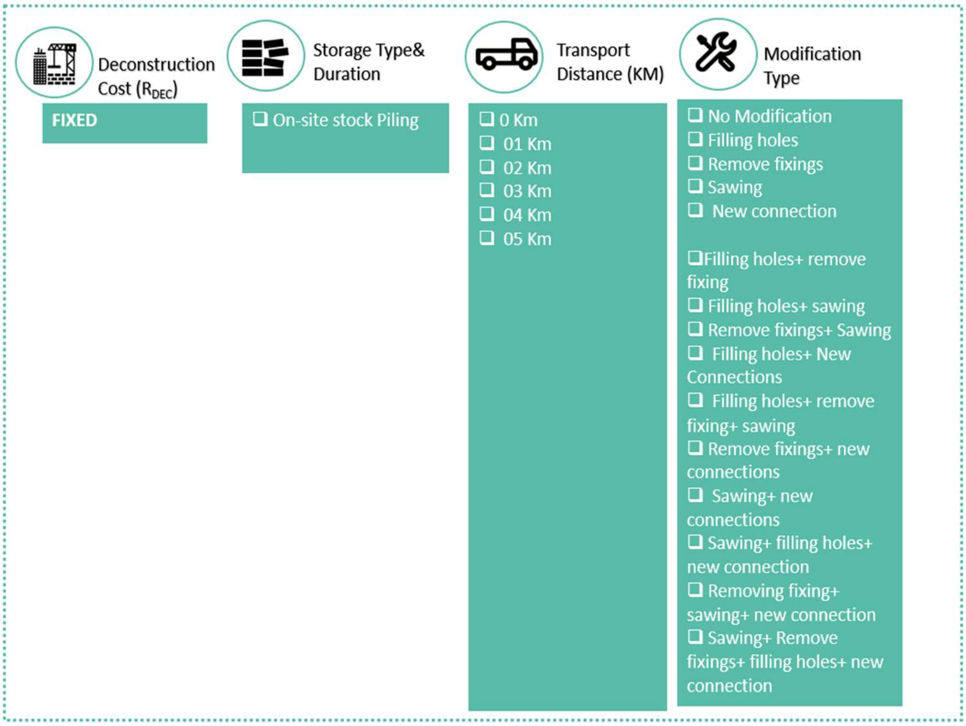


Figure 29: RS1_ System Boundary, Self-Illustration

- **Storage Type & Duration**: For direct on-site reuse, the secondary components can only be stored at the site by stock-pilling. Hence there is no storage cost in this scenario.
- **Transportation Distance:** Ideally on-site reuse would mean no transportation at all since the components are reused at the same site but in practice, it can mean that secondary products are harvested within a complex and reused. For instance, floors from building A are reused to construct building B located very close to building A. Therefore, the transportation boundary for RS1 is set from 0km (minimum) to 5km (maximum). It means that if a component is reused from one site to another site within a radius of 5km, it is considered an RS1 case.

Benefits:

- RS1 helps to overcome the issue of demand by consuming the secondary products on-site., i.e. there is already a reuse plan for the components before they are deconstructed. The new construction is designed to accommodate these secondary components.
- The architect can take into account the technical specification of the secondary components in the design stage itself, there is a high level of design consideration for reuse in RS1.
- It also limits the modification that the components need since the requirements are already known and the elements can be removed keeping them in mind. If needed, the modifications are carried out on the site itself.
- High quality of the products can be assured by using the same workers for deconstruction and construction process or involving the same contractor for the two jobs. It ensures proper handling, storage and recovery of elements as the workers are more cautious and thoroughly know how they want to reuse the component (Glias, 2013).
- Salvage value is maximum in the direct reuse, about 50% (Bradley, 2004)
- It is the most favourable scenario from environmental savings as the emissions from modification and transportation are minimum.
- The effort into supply chain management (SCM) is minimum. SCM refers to the flow of materials and services between different firms involved(da Rocha & Sattler, 2009). RS1 involves a minimum flow of materials and limited stakeholders as the reuse is on-site itself.

Challenges:

- It was found from interviews that direct on-site reuse is highly unlikely and least probable in most of the demolition projects. The new construction demands can rarely be met directly from on-site reuse of components from the old building. Often office buildings are demolition due to obsolescence, building with the same components requires great flexibility and creativity in design.
- The time of removal of the existing structure by deconstruction is a significant impediment for onsite reuse (Bradley, 2004).
- Another major challenge is material handling. One needs to ensure smooth disassembly and lifting of floor slabs, modifications (if needed) and stock-piling without conflict concerning space and timing. The sequence of storage is particularly important.
- The scheduling and order of deconstruction are also very challenging. Deconstruction and new construction rates must be well synchronized and planned. If deconstruction starts late then there will be delays in construction, if deconstruction finishes before then components need to be stored and extra logistics are needed.
- Constructing with the secondary component is a technical challenge because the design flexibility gets restricted as the design is now to fit the technical and physical properties of the components. The construction grid of the new project needs to be kept the same as that of deconstructed one which meant compromise on floor plans. For example, in a project "Recycling prefabricated building components for future generations", Germany, building components were moved to a new site for reconstruction. The construction grid

of the new project was kept the same as that of deconstructed one which led to the compromise on floor plans (Glias, 2013). Transportation and storage also need to be planned very carefully to synchronize the two processes: deconstruction to obtain the components and construction with these components.

5.4.2. RS2: Direct Off-site Reuse

It is the scenarios when the components are deconstructed from one site and taken to another site for reuse. It the second most efficient scenario after RS1 as there is already a demand for the deconstructed components at another site. However, it is expected that there is lesser or no design considerations in this case, unlike RS1. The architect may or may not design the building taking into account the specifications of the components to be disassembled. Transportation is crucial to ensure the correct sequence of arrival of components in case of off-site direct reuse. The specific components must arrive in the order of construction at the new site and within the stipulated time to avoid delays and operational overruns. The construction must follow deconstruction to avoid synchronization confusion.

System Boundary_ RS2: The system boundaries for deconstruction, modification and storage are same for RS1 and RS2, what differs is the transportation distance limits. Now the components can be transported from 6km up to 100km distance, i.e. the new construction site must be located within this radius to be considered as RS2 case. It is represented in figure 30.

- The deconstruction cost is fixed
- **Modification Type**: all types of modifications and combinations of modifications are included within the system boundary.
- **Storage Type & Duration**: For direct off-site reuse, the secondary components can only

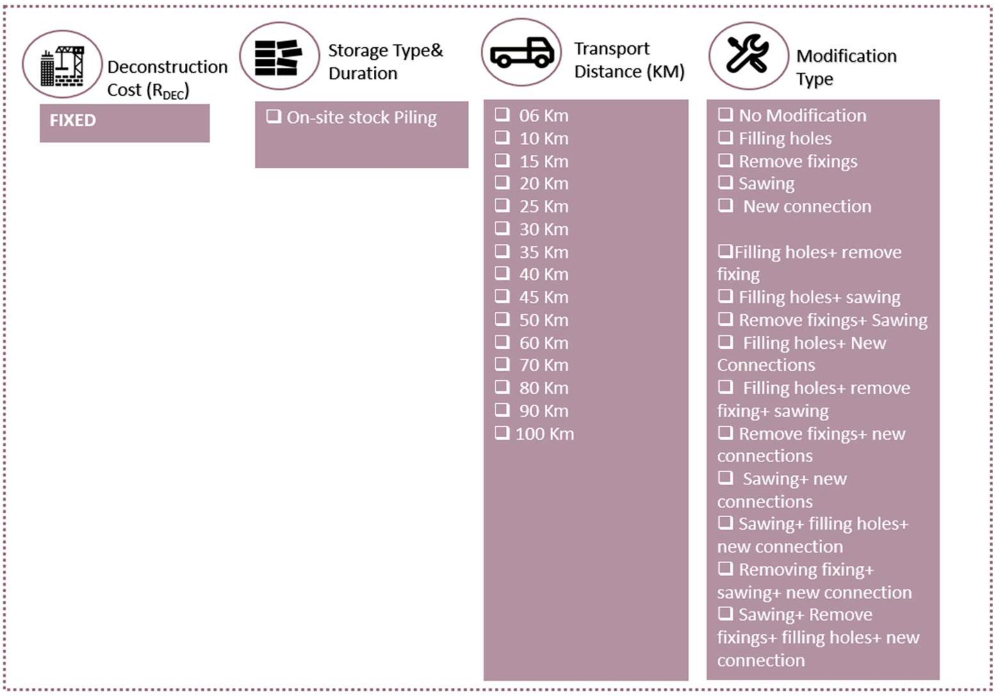


Figure 30:System Boundary_ RS2

be stored at the demolition or the construction site by stock-pilling. Hence there is no storage cost in this scenario.

- **Transportation Distance:** The transportation boundary for RS2 is 6km (minimum) to 100km (maximum)

Benefits:

- There is a demand for the deconstructed components beforehand.

- Modification costs are lesser than those of RS3, some modification might be needed as per the requirements of the new design. Mostly modified at the deconstruction site, rarely at the construction site
- There is no need to store the elements in the yard. If the demand and supply are not synched, the building can either be virtually stored or the components can be stock-piled.
- The salvage value of components is relatively higher than in RS3.

Challenges:

- The scheduling and order of deconstruction are very challenging. Elements should be deconstructed at the right time and in the correct order that they are needed for construction at the other site. Timely deconstruction is crucial to allow for modifications (if any) and risk-proofing the logistics.
- Large transportation distances can overrun the economic and environmental benefits.

5.4.3. RS3: Indirect Reuse

In this scenario, the products are recovered from the building, stored at a facility until a buyer is found and then delivered to the end-user. This is the least desirable scenario but it is most commonly seen in practice. The interviewees confirmed that often there is no buyer for a component before demolition, hence RS3 is more prevalent than RS1 and RS2.

System Boundary_ RS3: The system boundaries for deconstruction and modification are same as RS1 and RS2, what differs is the storage type and transportation distance limits. It is represented in figure 31.

- The deconstruction cost is fixed
- **Modification Type**: all types of modifications and combinations of modifications are included within the system boundary.

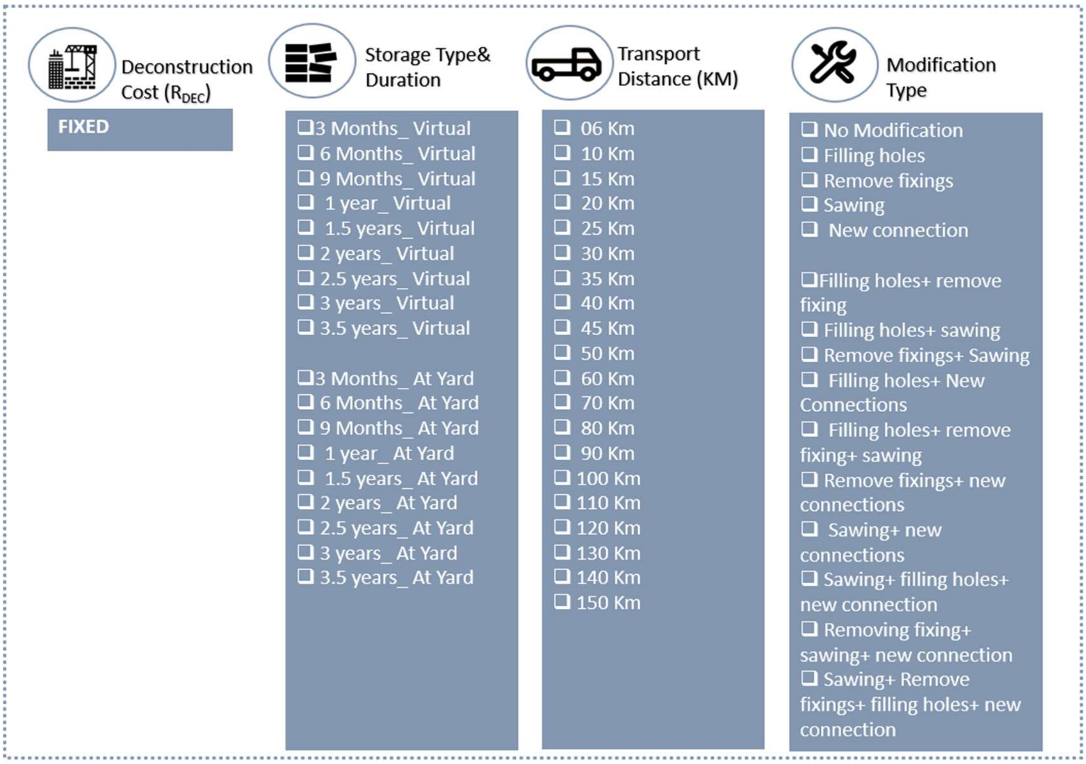


Figure 31: System Boundary_ RS3

- **Storage Type & Duration**: In RS3, the secondary components can either be stored at a yard or virtually at the deconstruction site. The storage duration range is assumed to be 3 months to 3.5 years. It is an optimistic limit since the owners do not want to pay the operational cost of a building for so long, however, this limit is taken to observe if the costs can be optimized such that virtual storage for 3.5 years can become feasible.

- **Transportation Distance:** The transportation distances depend on several factors such as the location of the new buyer, availability of regional market, type of reuse, etc. It varies for each case. The transportation boundary for RS3 is 6km (minimum) to 150km (maximum), includes the transportation from the deconstruction site to the storage to the end-user.

Benefits:

- The elements can be sufficiently checked for quality in the storage
- Deconstruction can happen independent of construction, there are no scheduling issues
- It also facilitates sale to multiple clients as they can buy the needed quantities and need not pay for all the components.

Challenges:

- Independent design and incompatible geometry can lead to modifications and rejection of a number of secondary products.
- Storage at a yard also incurs additional transportation distances.
- Modification costs are inevitable in this case as the demand is yet not known at the deconstruction time. A buyer has his requirements when he buys the components for reuse.
- The salvage value is lower for stored components. Sales to a secondary broker are about 20% of the retail price in the case of remanufacturing (Bradley, 2004)

Comparing the scenarios

It was concluded in the previous section that reuse is most feasible for RS1, then RS2 and least for RS3. It is important to understand the implications of this. Since there is no storage cost and lesser transportation for direct on-site reuse (RS1), the resultant reuse cost is lesser which makes it feasible. However, to make direct onsite reuse happen, one needs to ensure that reuse is well considered in the designing of the building itself, to ensure that once the building will reach its EOL, the components will be deconstructed and reused on the same site. Therefore, the concept of DFD becomes crucial here. However, for existing buildings, RS1 then becomes highly unlikely as these are not designed for disassembly. For a building which is not constructed with reuse in mind, RS1 is most likely to be economically unattractive as a great amount of effort goes into deconstructing a building not built for disassembly and ensuring its reuse at the same site. For indirect reuse, one is expected to modify the component to meet the requirement of the new constructions increasing the cost of reuse. Therefore, for existing building stock, the most viable option is to indirectly reuse the components (RS3). It implies that more cost is needed to modify than to transport or store the elements. In a hypothetical condition, if there is a buyer available to consume the secondary components when modified to his requirements, the owners should consider storing the elements for the feasible duration to find a buyer who wants no modification to the components. Hence, the criteria for deconstruction should not be the availability of a buyer in advance, it should rather be to find a buyer with no modification requirements even when elements are to be stored or transported.

6

FACTORS AFFECTING REUSE COST

This chapter discusses the various factors which are found to influence the reuse cost. The effect of each of the factors is identified. These factors are then quantified with the help of experts from practice and the best case and the worst-case are determined. A best-case is composed of “most desirable” types of factors whereas an in a worse case, all the factors are “least-desirable” and increase the reuse cost. Thereafter the strategy for making reuse profitable is discussed. This chapter answers the research sub-questions:

Q7. Which factors influence the reuse cost and how?
Q8. How to make reuse profitable?

6.1. Factors affecting Reuse Cost

There are various factors which affect the reuse cost of a project. It is crucial to analyze these controlling factors and quantify their effect on the reuse cost to make reuse an economically profitable case. With the help of available literature: (Dijk et al., 2000), (Bradley, 2001), Macozoma, 2001),(Philip, 2001), (Bradley, 2004),(Dorsthorst & Kowalczyk, 2005), (Glias, 2013),(Tatiya, 2016),(Hübner et al., 2017), (Bleuel, 2019), etc. following factors (figure 32) are found to affect the R_C.

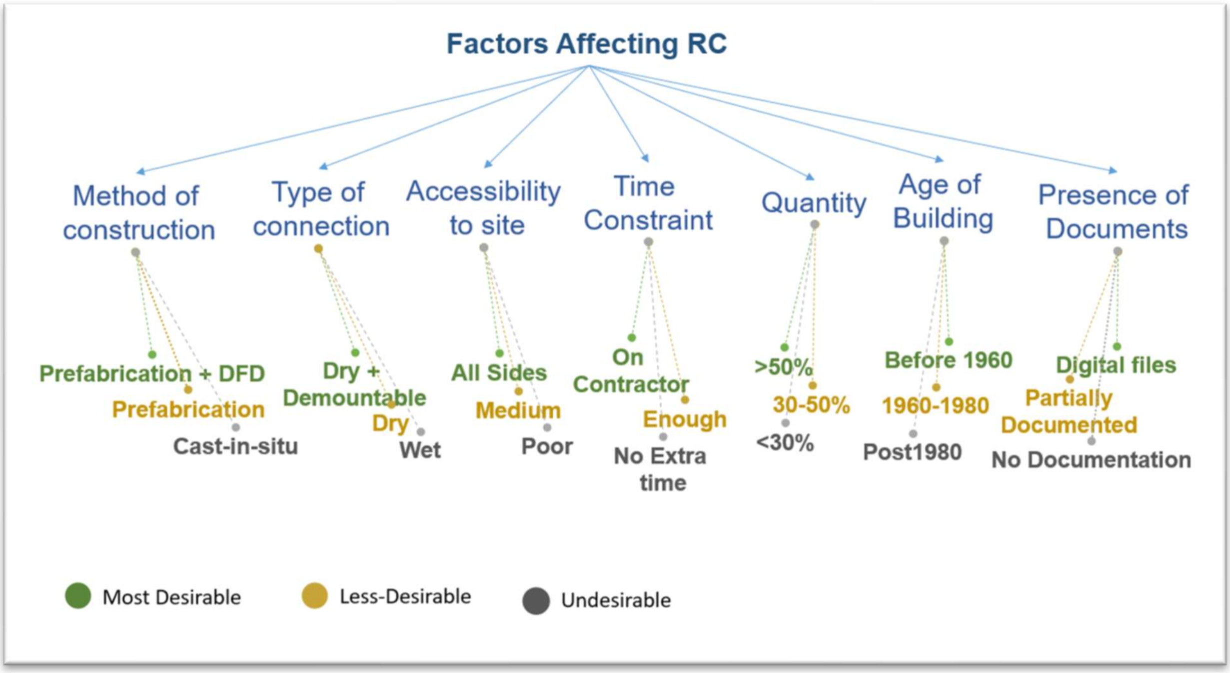


Figure 32: Factors Affecting Reuse Cost, self-illustration

- Method of Construction

- Type of Connection
- Time Constraint
- Accessibility to site
- Quantity (No.of floors)
- Age of the building
- Presence of documents

- **Method of Construction**: The structural components can either be cast in-situ or prefabricated. The method of construction determines the labour and equipment cost as the deconstruction of precast is better and easier than cast-in-situ (Dijk et al., 2000), (Philip, 2001),(Tatiya, 2016). The method of construction can be broadly divided into the following:
  - **Cast-in-situ:** It is undesirable to have cast-in-situ floors. In the case of cast-in-situ floors, a floor is a homogenous unit and densely reinforced. In-situ concrete is the toughest to deconstruct (Michael, 2018). To cut an element, it is to be sawed from all directions containing reinforcement. Another crucial decision to be made for the cast-in-situ floors is to decide the dimensions of the element to saw. If the element is cut out too short, it can get harder to find a reuse for it whereas a very long element poses logistical challenges. Therefore, it is important to find the optimum dimension.
  - **Prefabrication**: In prefabricated floors, the elements act as independent units and are to be cut only at the joints. They can only be modified into a smaller dimension, not the other way around. However, prefabricated components do not always guarantee easy disassembly for reuse. There can be chemical connections between the elements which hinder disassembly (Durmisevic et al., 2017). This is where the DFD component comes into play.
  - **Prefabrication+ DFD:** It is the most desirable method of construction for effective reuse as the prefabrication allows for disassembly, the process followed is simply the reverse of building construction (Dorsthorst & Kowalczyk, 2005). DFD concept reduces both the time and the cost of deconstruction. Amol Tatiya concluded in his research that DFD decreases the deconstruction time by 14% and the costs by about 11.5% (Tatiya, 2016).

Insights from interviews: Prefabricated elements are rather simpler to reuse as these are built according to certain load and have proven their capacity of withstanding this load. In the case of cast-in-situ, the optimized dimension of slabs which allows for minimum time and energy is not known, there is not enough data to plot such a pattern. For now, the slabs are recovered in smaller dimensions as these are easy to test, and also fulfil the weight requirements that the crane can lift. “750 tons is the limit of our crane and if we go higher than that we have to dig foundation to fix the crane which is added cost and effort. If more elements are needed, then it makes sense to call for a bigger crane as a break-even can be reached in that case “ (Interview 01, 2020).

- **Type of connection**: Before diving into the type of connections, it is important to understand how is a floor slab placed and connected to other components in a building. For cast-in-situ slab, the connections are homogenous, permanently developed by pouring concrete on the mesh reinforcement. However, this is not the case for prefabricated floors.

To understand the connections in a prefabricated floor slab, the example of an HCS is depicted in figure 33. Slabs are to be connected at the longitudinal interior joints and the transverse joints. These interior joints are filled with concrete grout. Slabs are supported by THQ beams when they are placed next to each other. A tension rod of two strands binds all the HCS slabs together.

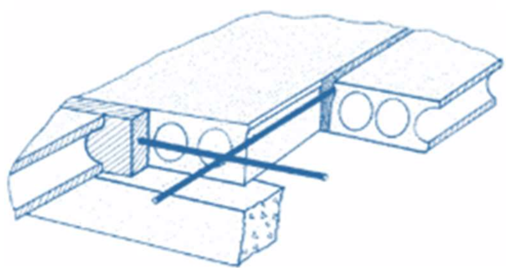


Figure 33: S-S Connections in HCS: source: (Engstrom, 2008)

To connect the slabs to the edge elements/end supports, the slabs are placed on console. Tie bars are attached to the wall and placed between the joints of the core. In the longitudinal direction of the wall, one or two tie bars are placed at the end of the core and attached to the wall. In the perpendicular direction, at two places of each floor bay, strips are anchored into the core as well as the walls. There are various ways of developing these connections. Each of these connection types has different suitability for reuse as summarized in table 5.

Table 5: Connection suitability for reuse, source (Hradil et al., 2014)

Connections	Suitability	Note
Cast and reinforced connections	sometimes suitable	Usually will damage both elements and connection steels.
Welds	mostly suitable	Usually can be replaced with new welds and connection steels.
Bolts	suitable	Usually easy to open without damaging the elements.

Type of connections affect the deconstruction cost and time, repair costs and also the type of equipment used. Disassembly is not affected by the size, weight or volume of the component but it is affected by the connections of the components which are most important for determining the economic costs (Bleuel, 2019). When the floor is casted-in-situ, the connections made are often chemical connections developed with reinforcement and concrete mortar. They get embedded in concrete and therefore need to be broken with chiseling or cut with a diamond saw. The saw also cuts tie bars from the panels. As a result, the old connections are destroyed and new connections are to be developed for reusing the slab. On the other hand, the prefabricated elements are highly independent and connected only at the joints. However, they do not always guarantee easy disassembly for reuse as there can be wet connections between the elements. The type of connections can be broadly divided into the following:

- **Dry connections:** include connections with fitting and fasteners like bolts, screws, etc. These are favoured for efficient recovery of the components with minimum damage. Bolted connections provide easy disassembly but they are often fixed in place by grouting or with finishing layer.
- **Dry + Demountable connections:** these are the most desirable types of connections enabling components to be safely and cheaply removed for reuse. These connections are designed with future disassembly in mind. They are dry but also ensure minimum damage in disassembly. These connections are designed such that there is a minimum amount of different connections made with external fixing device. During deconstruction, one can easily saw through this external attachment while keeping the main element safe.

- **Wet connections:** involves the use of adhesives and sealants like epoxies, cast-in-place concrete, etc. Grouting reinforcement bars at the site is a typical example of a permanent chemical bond. These connections when broken for recovering the element, often leads to damage and requires repair before reuse (Tatiya, 2016). There is then an additional cost of redeveloping the connections for reuse. Even in the case of prefabricated elements, the connections are not designed to be deconstructed and are thereby destroyed. Hence, chemical connections are least desirable for efficient deconstruction.

- **Time constraint**: Time constraint is a crucial factor which can affect deconstruction.

Strict deadlines set by clients can hinder effective deconstruction. Often the owner wants to get rid of the old building at the earliest to start the new project. For a normal deconstruction aimed at recovering components, deconstruction consumes the highest amount of labour time, about 26% on an average. However, in case there is a shortage of time for deconstruction, most of the labour is redirected to deconstruction activity consuming as much as 47% of the total labour hours (Bradley, 2004). This diversion of labour results in fewer labour hours in the processing and handling of components. When the components are not processed and modified on-site, they have to be modified at a later stage again resulting in increased modification costs. To minimize modification, the components need careful dismantling, however, time constraints do not allow for it. It results in recovery of lesser components at increased damage and ultimately higher repair costs. In the case of over-run, it can lead to a breach of agreements as well (Macozoma, 2001).

Reuse is most profitable when enough time is allocated to find a buyer. The most desirable option is to involve the demolition contractor in the early stages of permit and planning and let the contractor ask for the time he needs i.e. leave it on the discretion of the contractor. A more likely but less desirable way is to provide some time extra to the contractor to explore feasible reuse opportunities and the least desirable is to allow him no extra time and instead ask him to operate within the demolition time frame.

Insights from the interviews:

Deconstruction for reuse is possible only when the client allows enough time for it. If there are time constraints posed by the owner/client, the building is simply demolished to deliver the project in time. In projects where components are to be reused, the contractor always asks for more time, roughly 4 weeks depending on the type of project, to find reuse possibility. However, the chances of deconstruction for reuse are greater if there is no or lesser time constraints posed by the client. For example, in case of projects where the owner has an empty standing building and he cannot build on it because of permit issues, the keys are handed to the demolition contractor for survey and removal of hazardous materials. Since there are no time constraints, it gives the contractor bigger opportunities to find buyers for reuse. Hence, when time is not an issue, one can look at a building differently. In case there are high time constraints, the contractor can deal with it by increasing the labour and machinery on the site. However, there is an optimum level up to which one can increase the resources, beyond that it turns uneconomic and logistically difficult.

- **Presence of Documents**

If component details like type, strength and connections are well known from the documentation, it can be accordingly removed. Knowing what is to be deconstructed reduces the damage in execution and thereby the modification costs. Deconstruction planning can be more precise if proper documents are available. It can further reduce the uncertainty in execution and facilitate precise profit and risk calculations. The most desirable is to have a complete digital model of the building, however, it is not possible for the older constructions as digitization such as BIM and digital building passports are quit newer concepts. The most likely option is to find partial documentation but one has to do the on-site investigation to ensure that the drawings are consistent with the details on site.

Insights from the interviews:
Documentation is very important. Having the documents in place reduces the time and effort that goes into the investigation, the risk of accidents and unplanned collapse. However, for the buildings reaching EOL now, there is no documentation available. The contractor needs to investigate how the building is made to see how the building comes apart. Presence of documents does not matter much for a traditional demolition project but for projects involving reuse, one has to test compulsorily for quality if there is no documentation. If historical data of the building is well documented and preserved, there is no need to test the components. It is then easy to get a good idea of loading conditions of a building built as per standards.

- **Accessibility to site**

It is the access to the site and individual building components. High accessibility implies ease of reaching out to the site and the components for the disassembly process whereas low accessibility implies space restrictions for equipment, resulting in high labour costs to prepare the site and handle material. It determines the equipment which can be used on the site and ultimately the method of deconstruction and the quantities of components to be deconstructed. For instance, the dimension and the number of components to be deconstructed from a low accessibility site depends on the size and capacity of crane that can be brought on-site for operation. In a poorly accessible site, it is often less probable to modify and store the components onsite. Hence the components are deconstructed and modified for reuse elsewhere resulting in increased costs**.**

Insights from the interviews:
It is rarely the case that the site accessibility is very critical. For example, when the project is very close to the train track, about half a meter distance. In such a case the work can be done only when there is no train traffic. Even in this case, the building should be divided into parts and the part facing the rail track should be kept for last. If the building is within a city centre than you have more things to take into account the working hours, the maximum loads, parking arrangements of the people. Other health concerns such as vibrations produced by demolition can cause harm to the stability of the buildings nearby, the dust and sound produced are to be controlled so it does not harm the neighbourhood. In a congested area, you have to schedule the loading of the debris or components in the non-peak hours. Since bigger machines cannot be installed, it takes longer time to deconstruct with smaller equipments but it can be scaled up with more manual labour. Site accessibility also determines the level of on-site separation of waste. For a congested space, the level of separation of different materials is low. When there are no space restrictions, one can put as many as 5-6 separate containers for segregation of different waste streams but for congested sites, there can maximum be only 2 containers. It then affects the recycling efficiency also.

- **Quantity**

Quantity is the number of elements recovered from deconstruction. The effect of quantity on the deconstruction cost depends on the value of the product. Without knowing the value of the product, the effect of quantity is difficult to estimate. For instance, in the case of a product with high demand, deconstruction in smaller quantities also turn economic. However, it does not apply to the secondary product which has no demand or lower value. In that case, high the quantity of recoverable in a building (>50% total products in the building), greater is the business case. If the recoverable are lesser than 30%, contractors are hesitant to find a business case for this little quantity. Higher quantity also demands greater site storage and more organized logistics (Tatiya, 2016).

Insights from the interviews
Quantities do not matter when deconstruction is provided as a service and the components remain under the ownership of the client. When there is a project involving less than 30%

deconstruction, then the best practice is to quote separately for demolition and deconstruction activity. For example, for a demolition project of 4 warehouses, one of which is to be deconstructed for reuse. One should now make a separate calculation for it and put in the extra labour hours into it. However, if the contractor claims the components and sells them himself, then the quantities and salvage value affect the final quote of the contract. Quantity as such does not matter, what matters is the value of the secondary component and the demand for it. If there are buyers for the components, then they are deconstructed irrespective of the quantity. However, if the amount of the secondary product is very less, it gets hard to find a buyer and it is therefore uneconomic to recover it.

- **Age of the Building**

It acts as a measure of the quality and the type of the materials within the building (Tatiya, 2016). For instance, one can expect to find hazardous materials in old buildings (Hübner et al., 2017) whereas most of the buildings from past 50 years have composite materials used in their construction (Bradley, 2004). Buildings constructed before 1960, are often built with monolithic materials like wood, steel or even concrete. The contractors prefer to deconstruct these buildings for reuse as then they do not have to deal with the huge number of composites that are now used in the buildings. Old buildings are often over-dimensioned and have an aesthetic value which eventually increases the salvage value.

Insights from the interviews

More than age, it is about the quality of the components in the building which determine reuse cost. However, if it is an old building, the elements will have historic value, a bigger market of buyers and no requirements of quality assurance. Over-dimensioning will further add to the flexibility of reuse. For reuse, it is useful to have buildings of pure materials like stone, glass and wood. Buildings built after the 1960s contain composite materials like PIR foams attached to the floors. Separating this foam from the floor requires time and creates environmental nuisance as the foam flies in the air when scraped on-site making reuse tough.

6.2. Quantifying the effect of factors

Having identified these factors, the next step is to assess which factors are more controlling or have a greater effect on the reuse cost. This information is not available in the literature as all the determinants are qualitative in nature. To quantify their effect on R_C, a multi-criteria decision making (MCDM) approach is adopted. To do so, a tool called the Analytical Hierarchy Process (AHP) is used.

Analytical Hierarchy Process (AHP): it is a multi-criteria decision-making tool devised by Thomas Saaty in 1980. In AHP, a priority scale is formed by pairwise comparison of various criterion based on the judgement of the expert who derives the priority scale (White, 1987) (Saaty, 1987). It sets the priority to each of the parameters by assigning them weight factor based on the judgement of the decision-maker (Westhoff, 2018). In other words, through AHP, the given factors can be assigned individual weights on a priority scale by comparing them pairwise. Expert judgement is used to compare them. Therefore, interviews are conducted with various stakeholders such as demolition contractors, project leaders, cost estimators, etc. to compare and weight these factors through AHP. AHP is applied to a problem in four systematic steps:

- **Define the problem**: How do these factors affect R_C? Which factors have a greater impact than others and by how much?

- **Structure** of the decision hierarchy from the top with the goal (figure 34)

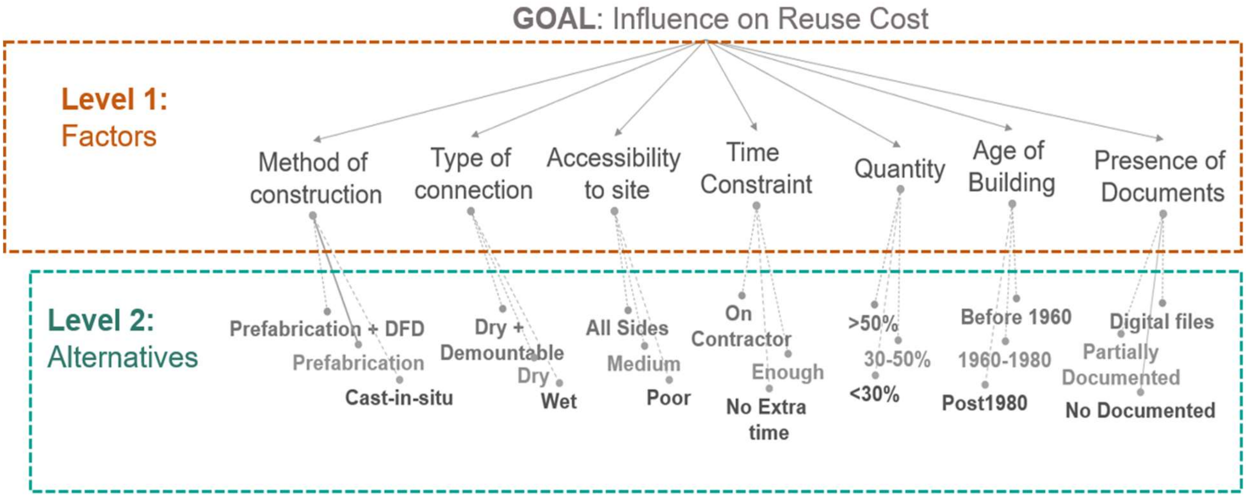


Figure 34: Decision Hierarchy

- **Construct a pairwise comparison matrix**

In a comparison matrix, the parameters are arranged in a matrix (i,j) where i is the value in the column and j is the parameter in the row, i.e. the same parameters in the column as the row. Then each of the parameters in the column is compared to each of the parameters in the row. The comparison is made such that the question asked is when considering one parameter in the column and comparing it with parameter one in the row, which of the two satisfies the focus more and is more significant than the other. The transpose values are generated by the reciprocals (Table 6).

Table 6: Comparison Matrix, Self-illustration

Comparison Matrix (I,j)		j1 Method of construction	j2 Type of connections	j3 Time Constraint	j4 Accessibility to site	j5 Quantity (no of floors)	j6 Age of the building	j7 Presence of Documents
i1	Method of construction	i1j1	i1j2	i1j3	i1j4	i1j5	i1j6	i1j7
i2	Type of connections	i2j1	i2j2	i2j3	i2j4	i2j5	i2j6	i2j7
i3	Time Constraint	i3j1	i3j2	i3j3	i3j4	i3j5	i3j6	i3j7
i4	Accessibility to site	i4j1	i4j2	i4j3	i4j4	i4j5	i4j6	i4j7
i5	Quantity (no of floors)	i5j1	i5j2	i5j3	i5j4	i5j5	i5j6	i5j7
i6	Age of the building	i6j1	i6j2	i6j3	i6j4	i6j5	i6j6	i6j7
i7	Presence of Documents	i7j1	i7j2	i7j3	i7j4	i7j5	i7j6	i7j7

- Comparison scale: The judgements are made on a scale of 1-9 as shown in figure 35. The scale is arranged in increasing order of importance. An as explained in the figure below.

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Figure 35: Comparison Scale, source (Saaty, 1987)

- **Interview relevant actors:** In this step, the interviewees are asked to fill the comparison matrix. A total of eight interviews were conducted out of which five interviewees had filled the comparison matrix. The detail of each of these responses can be found in appendix 1. Following steps are followed:
  - setup the matrix and explain the goal of the exercise, the meaning of various factors, AHP functioning and scoring system to the interviewees.
  - Ask questions: Then ask them to use their judgements to compare the factors in a pairwise fashion and assign weights from the fundamental scale. It is important to ask the question correctly as the framing of the question can influence the judgements and hence the priorities (Saaty, 1987). For instance, for the given comparison matrix the question is
    - i. For (i1,j2): How much more important is the method of construction in determining reuse cost over the type of connections?
    - ii. For (i1,j3): How much more important is the method of construction in determining reuse cost over time constraint to deconstruct?
    - iii. For (i1,j4): How much more important is the method of construction in determining reuse cost over accessibility to site?
    - iv. For (i1,j5): How much more important is the method of construction in determining reuse cost over quantity of secondary components?
    - v. For (i1,j6): How much more important is the method of construction in determining reuse cost over the age of the building?
    - vi. For (i1,j7): How much more important is the method of construction in determining reuse cost over the presence of documents?
    - vii. For (i2,j3): How much more important is the type of connections in determining reuse cost over the time constraints?
    - viii. For (i2,j4): How much more important is the type of connections in determining reuse cost over accessibility to site?
    - ix. For (i2,j5): How much more important is the type of connections in determining reuse cost over the number of secondary components?

x. For (i2,j3): How much more important is the type of connections in determining reuse cost over the age of the building?

xi. For (i2,j3): How much more important is the type of connections in determining reuse cost over the presence of documents?

Similarly, questions are formulated for i3,i4,i5, i6 and i7. The diagonal values of the matrix are unity whereas the lower half of the matrix is filled by taking the reciprocals of the corresponding values in the upper half (Schmidt et al., 2015), (Saaty, 1987). For instance, the value of cell i4j1 = 1/i1j4. The answers are then filled in the matrix as shown in table 7.

Table 7:Example of filled Comparison Matrix from Interview-02

Comparison Matrix (I,j)		j1 Method of construction	j2 Type of connections	j3 Time Constraint	j4 Accessibility to site	j5 Quantity (no of floors)	j6 Age of the building	j7 Presence of Documents
i1	Method of construction	1,000	1,000	9,000	7,000	9,000	7,000	3,000
i2	Type of connections	1,000	1,000	9,000	1,000	9,000	7,000	3,000
i3	Time Constraint	0,111	0,111	1,000	1,000	1,000	3,000	3,000
i4	Accessibility to site	0,143	1,000	1,000	1,000	1,000	5,000	0,200
i5	Quantity (no of floors)	0,111	0,111	1,000	1,000	1,000	0,333	0,333
i6	Age of the building	0,143	0,143	0,333	0,200	3,000	1,000	1,000
i7	Presence of Documents	0,333	0,333	0,333	5,000	3,000	1,000	1,000
	Sum	2,841	3,698	21,667	16,200	27,000	24,333	11,533

- Once the matrix is filled, a **normalized matrix** is generated (Table 8). The sum of each column is calculated in the comparison matrix. Each entity in the matrix is divided by the sum of its respective column to get the normalized matrix.

Table 8: Example of Normalized Matrix from Interview-02

Normalized Matrix		j1 Method of construction	j2 Type of connections	j3 Time Constraint	j4 Accessibility to site	j5 Quantity (no of floors)	j6 Age of the building	j7 Presence of Documents	Local Weights (Row Average)
i1	Method of construction	0,352	0,270	0,415	0,432	0,333	0,288	0,260	0,336
i2	Type of connections	0,352	0,270	0,415	0,062	0,333	0,288	0,260	0,283
i3	Time Constraint	0,039	0,030	0,046	0,062	0,037	0,123	0,260	0,085
i4	Accessibility to site	0,050	0,270	0,046	0,062	0,037	0,205	0,017	0,098
i5	Quantity (no of floors)	0,039	0,030	0,046	0,062	0,037	0,014	0,029	0,037
i6	Age of the building	0,050	0,039	0,015	0,012	0,111	0,041	0,087	0,051
i7	Presence of Documents	0,117	0,090	0,015	0,309	0,111	0,041	0,087	0,110

- **Use the priorities obtained from the comparisons to obtain weights:**
  Once the normalized matrix is formulated, the local weights are to be obtained for each of the factors. This is done by taking the average of the elements in each row as depicted in the table above.
- **Check the consistency of judgement**: It is done by calculating the Consistency Ratio (C.R). A judgement is found to be consistent if the value of C.R < 0.1, i.e. a 10% inconsistency. If the CR is greater than 0.1, the judgements are inconsistent and cannot be used to make rational decisions. Hence, it is discarded. To calculate the consistency ratio, first λ_{max} from the equation [AX= λ_{max} X] where A is the comparison matrix and X is the matrix of local weights. Having calculated AX matrix, λ_{max} is calculated as the average of the ratio of respective components of the AX matrix and the matrix X. Thereafter consistency index (C.I) is calculated by the following formula:

$$C.I = (\lambda max - n)/(n-1)$$

$$C.R = C.I / R.I$$

If C.R< 0.1, Consistent else Inconsistent judgement

Where,
n= no of criterion= 7 factors in the given case.
R.I = Random Index value. For n= 7, R.I is found to be 1,32 (White, 1987).

Table 9: Judgement Consistency of Interviews

S.No	Consistency Ratio (C.R)	Is the judgement consistent	Eligible for weighing the factors?
Interview 02	0,233	Inconsistent	NO
Interview 03	0,729	Inconsistent	NO
Interview 04	**0,060**	**Sufficiently Consistency**	**YES**
Interview 05	0,382	Inconsistent	NO
Interview 06	**0,073**	**Sufficiently Consistency**	**YES**

When tested for consistency, only two of the interviewee's judgements passed the consistency test. The summary of the five interviewees is shown in table 9.

- **Calculate the average local weights**
  The average local weights (Table 10) are calculated for the judgements that passed the consistency tests, ie, interview 04 and 06.

Table 10: Average Local Weights

Factors	Local Weights (Interviw_04)	Local Weights (Interviw_06)	Average Local Weights
Method of construction	0,231	0,160	**0,195**
Type of connections	0,367	0,132	**0,250**
Time Constraint	0,141	0,397	**0,269**
Accessibility to site	0,040	0,076	**0,058**
Quantity (no of floors)	0,036	0,116	**0,076**
Age of the building	0,058	0,038	**0,048**
Presence of Documents	0,126	0,082	**0,104**

- **Normalize weights for second-level factors**

The second level factors or the alternatives are scaled from 8(most desirable) to 5 (medium) to 3(least desirable) level. These equivalent weights are then normalized on the most desirable alternative to obtain the normalized weights as shown in table 11.

Table 11: Second Level Alternatives

Equivalent weights	Normalized weights	Method of construction	Type of connections	Time Constraint	Accessibility to site	Quantity (no of floors)	Age of the building	Presence of Documents
8,000	**1,000**	Prefabricated+ DFD	Dry + Demountable	At discretion of contractor	All side	>50%	Before1960	Complete Digital files
5,000	**0,625**	Prefabricated	Dry	Enough to fnd buyer (20% extra)	Medium	30-50%	1960-1980	Partially documented
3,000	**0,375**	Cast-in-situ	Wet Connections	No extra time	Poor	<50%	Post 1980	No documentation

- **Calculate net weightage:** The net weightage is calculated for each of the level two alternatives by multiplying the average local weights obtained to the normalized weights for second-level factors. This gives the net weightage which can be directly applied to the reuse cost to see its effect.

Results: The results as shown in figure 36, suggests that time constraint has the highest effect on R_C (27%), closely followed by type of connection (25%). Thereafter method of construction (19%), presence of documents (10%), quantity (8%), accessibility to site (6%) and age of building (5%) affect the reuse cost. Table 12, shows the distribution on the second-level factors. The signs (+/-) in front of the factors are indicative of their eventual effect on the reuse cost. For instance, a "prefabricated+ DFD" construction reduces the cost and hence it has a negative factor assigned to it whereas cast-in-situ slabs are difficult to take out and increase the reuse costs and hence the positive sign attached to it.

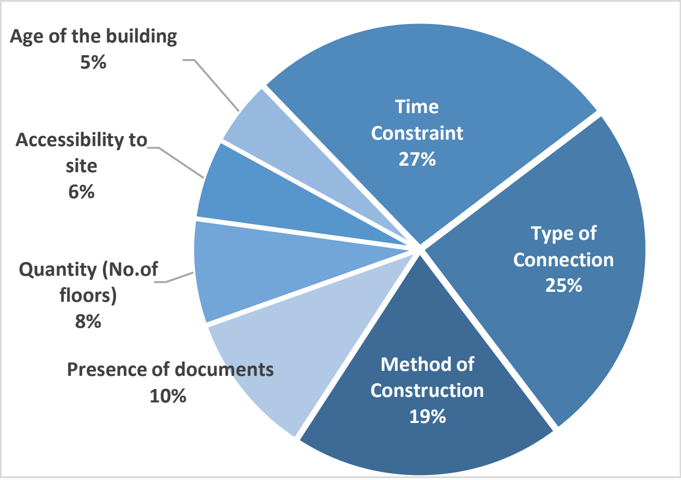


Figure 36:Effect of factors on the reuse cost (%)

Table 12: Net Weightage

Factor	Net Weightage
Time Constraint	**0,269**
At discretion of contractor	-0,135
Enough to find buyer (20% extra)	-0,084
No extra time	0,050
Type of connections	**0,250**
Dry + Demountable	-0,125
Dry	-0,078
Wet Connections	0,047
Method of construction	**0,195**
Prefabricated+ DFD	-0,098
Prefabricated	-0,061
Cast-in-situ	0,037
Presence of Documents	**0,104**
Complete Digital files	-0,052
Partially documented	-0,032
No documentation	0,019
Quantity (no of floors)	**0,076**
>50%	-0,038
30-50%	-0,024
<30%	0,014
Accessibility to site	**0,058**
All side	-0,029
Medium	-0,018
Poor	0,011
Age of the building	**0,048**
Before1960	-0,024
1960-1980	-0,015
Post 1980	0,009

6.2.1. Best-Case

In a best-case scenario, all the factors positively affect the costs i.e, they reduce the reuse cost by being the "most desirable" type. The reuse cost is reduced by 50.1% in a best-case scenario as shown in figure 37. However, in practice, it is highly unlikely to have all these factors in the most desirable combination. It would mean to deconstruct a building where there are no time constraints i.e. at the **"discretion of the contractor"**; the connections are **"dry+**

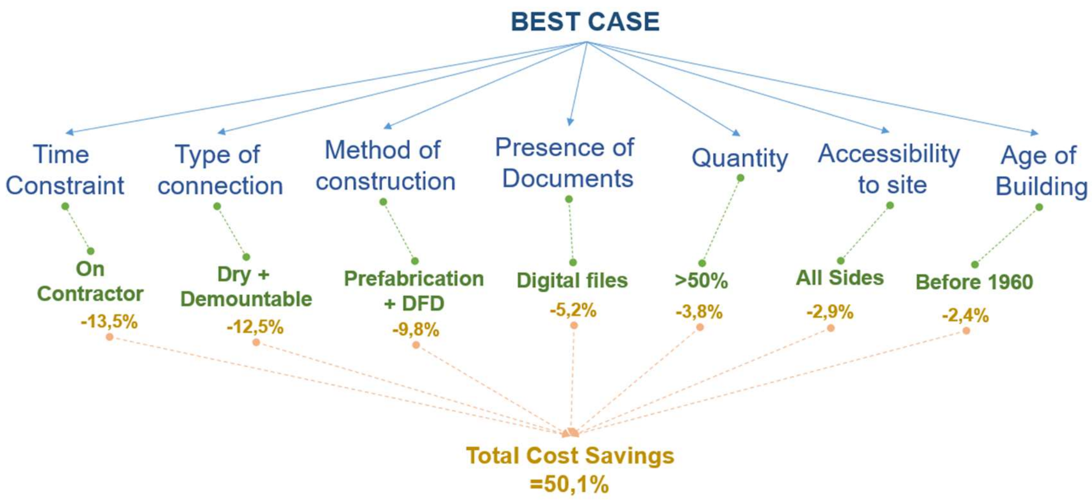


Figure 37: Best Case

demountable"; the construction is **"prefabricated+ DFD"**; there exists "**complete digital**" documentation of the building and its components with **over 50%** of recoverable floors and the site has **all side accessibility** with a homogeneous construction **(before 1980)**. Hence the scenario is highly unlikely to occur in practice.

6.2.2. Worst-Case

In a worst-case scenario, all the factors negatively affect the reuse costs i.e, they increase the reuse cost by being "undesirable". The reduce cost (Rc) is increased by about 18.7% in the worst case as shown in figure 38. It would mean to deconstruct a building where there is "**no extra time"** allocated for deconstruction; the connections are **"wet"**; the construction is **"cast-in-situ"**; there exists "**no documentation**" of the building; the quantity of recoverable components is "**<30%"** and the site has "**poor accessibility**" with a heterogeneous construction **(post-1980)**. Like the best-case, the worst-case scenario is also unlikely to occur in practice.

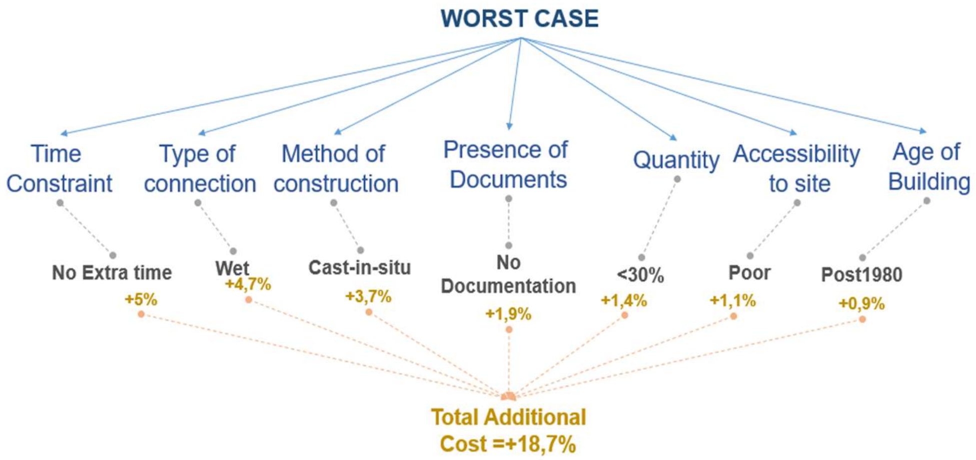


Figure 38: Worst- Case

6.3. Profitable Reuse

A combination of policy instruments is needed to make reuse profitable. For instance, environmental policies like the landfill ban, Provincial Environmental Ordinances and Building Material Decree are found to have a positive impact in reuse adoption (Dijk et al., 2000). Tests on increasing virgin materials taxes and/or gravel taxes across Europe suggests that it is profitable to promote reuse(Commission European, 2016). To ensure effective reuse, secondary materials should be made available at competitive prices. It can be achieved by differentiating landfill taxes such that higher taxes are set for reusable products. Having identified the products which need policy support, these taxes can be regulated. Technical and financial support such as tax deduction for salvaged materials, loans for land acquisition to secondary product businesses has a significant role in the creation of secondary markets, employment opportunities and training of labour (Bradley, 2001).

There are two ways to optimize the reuse costs such that it becomes economically profitable. One way is to increase the budget allocated for reuse by extending the system boundary and the other way is to optimize the process for worse case. Each of these strategies is discussed below in detail:

6.3.1. Optimize for the worst-case scenario

The aim to optimize the worse-case is to identify under which "least-desirable" factors, the reuse case is still economic. The optimization is done with the What-if Analysis in Microsoft Excel using the Solver function. The aim is to optimize in such a way that the "Total Additional

Cost" is reduced to 0 while maintaining most of the factors as least desirable. When all the factors are "least-desirable", there is an 18.7% (Table 13) additional cost to be made which makes reuse uneconomic. However, in an optimized worse-case, there are no additional costs. It implies that one or more of the factors cannot be "least-desirable", they need to be optimized to either "most desirable" or "desirable levels" to attain no additional cost.

Method Used: Out of all the seven factors, the only controllable factor which a stakeholder can choose himself is the "Time constraint". It also has the highest impact on the reuse cost (27%) as found through AHP analysis. Therefore, it is fed as a variable element to the Solver to optimize the additional costs to a minimum. However, in practice, it is not possible to have ample time in every project. As learned from the interviews, there exist strict restrictions on time. Therefore, optimization is also performed to explore the solution when time constraint is not most-desirable but desirable and least desirable. In this case, the time constraint is given and factors are optimized in reverse order of importance i.e. first we try to optimize with less important factors starting with the age of building followed by accessibility and so on. It helps to explore conditions under which important factors can be least-desirable and reuse can still be feasible.

Table 13: Worst-Case

Factor		Net Weightage
Time Constraint	No extra time	0,050
Type of connections	Wet Connections	0,047
Method of construction	Cast-in-situ	0,037
Presence of Documents	No documentation	0,019
Quantity (no of floors)	<30%	0,014
Accessibility to site	Poor	0,011
Age of the building	Post 1980	0,009
Total Additional Cost		0,188

- **Optimizing with Most- Desirable Time Constraints:**

If the time constraint is changed from least-desirable to most-desirable, the worst case optimization is reached as it results in an additional cost of +0.2% which is approximately 0. For a more precise or negative total additional cost, age of the building can be changed to a desirable state which results in 2.2% savings in the total cost (Table 14).

Table 14: Optimizing with most desirable time constraint

Factor		Net Weightage
Time Constraint	At discretion of contractor	-0,135
Type of connections	Wet Connections	0,047
Method of construction	Cast-in-situ	0,037
Presence of Documents	No documentation	0,019
Quantity (no of floors)	<30%	0,014
Accessibility to site	Poor	0,011
Age of the building	Post 1980	0,009
Total Additional Cost		0,002

Factor		Net Weightage	Optimizing for age (desirable)
Time Constraint	At discretion of contractor	-0,135	-0,135
Type of connections	Wet Connections	0,047	0,047
Method of construction	Cast-in-situ	0,037	0,037
Presence of Documents	No documentation	0,019	0,019
Quantity (no of floors)	<30%	0,014	0,014
Accessibility to site	Poor	0,011	0,011
Age of the building	Post 1980	0,009	-0,015
Total Additional Cost		0,002	-0,022

- **Optimizing with Desirable Time Constraints:**

When it is not possible to allow time at the discretion of the contractor, the case needs to be optimized for "desirable time constraints". First, the time constraint is changed from "No extra time (least desirable)" to "Enough to find a buyer- 20% extra (desirable). The effect can be seen in table 15. However, there still remains an additional 5.3% cost. It means that providing desirable time is not enough while maintaining all other factors at "least-desirable". One needs to then optimize the age of building to reach 0% cost addition by first optimizing for desirable condition, "1960-1980". However as seen in table 16, this results in net additional cost of 2.9% age of building, then the most-desirable i.e. before 1960 is used which also fails to achieve

Table 15: Optimizing with desirable time constraints

Factor		Net Weightage
Time Constraint	No extra time	0,050
Type of connections	Wet Connections	0,047
Method of construction	Cast-in-situ	0,037
Presence of Documents	No documentation	0,019
Quantity (no of floors)	<30%	0,014
Accessibility to site	Poor	0,011
Age of the building	Post 1980	0,009
Total Additional Cost		0,188

→

Factor		Net Weightage
Time Constraint	Enough to find buyer (20% extra)	-0,084
Type of connections	Wet Connections	0,047
Method of construction	Cast-in-situ	0,037
Presence of Documents	No documentation	0,019
Quantity (no of floors)	<30%	0,014
Accessibility to site	Poor	0,011
Age of the building	Post 1980	0,009
Total Additional Cost		0,053

0% target. Hence, there is a need to optimize for accessibility factor. When selecting the "desirable accessibility" i.e. "medium", the total additional cost turn -0.9%. Hence the case is optimized.

Table 16: Less desirable time constraint+ most desirable age

Factor		Net Weightage	Optimizing for age (desirable)		Optimizing for age (most-desirable)	
Time Constraint	Enough to find buyer (20% extra)	-0,084	Time Constraint	-0,084	Time Constraint	-0,084
Type of connections	Wet Connections	0,047	Type of connections	0,047	Type of connections	0,047
Method of construction	Cast-in-situ	0,037	Method of construction	0,037	Method of construction	0,037
Presence of Documents	No documentation	0,019	Presence of Documents	0,019	Presence of Documents	0,019
Quantity (no of floors)	<30%	0,014	Quantity (no of floors)	0,014	Quantity (no of floors)	0,014
Accessibility to site	Poor	0,011	Accessibility to site	0,011	Accessibility to site	0,011
Age of the building	Post 1980	0,009	1960-1980	-0,015	Before1960	-0,024
Total Additional Cost		0,053		0,029		0,020

- **Optimizing with Undesirable Time Constraints:**

It is most challenging to optimize for least desirable time constraint i.e. when there is no extra time allocated for doing the job. Several factors are to be optimized for this, starting from the least important one. The optimization i.e. the point where the additional costs are no longer there is achieved at the desired level of "the presence of documents" having reached the most-desirable levels of "age"; "accessibility" and "quantity"."

Table 17: Less desirable time constraint+ most desirable age+ desirable accessibility

Factor		Net Weightage	Optimizing for age (desirable)	Optimizing for age (most-desirable)	Optimizing for assessibility (desirable)
Time Constraint	Time Constraint	-0,084	-0,084	-0,084	-0,084
Type of connectio	Type of connections	0,047	0,047	0,047	0,047
Method of constructi	Method of construction	0,037	0,037	0,037	0,037
Presence of Document	Presence of Documents	0,019	0,019	0,019	0,019
Quantity (no of	Quantity (no of floors)	0,014	0,014	0,014	0,014
Accessibility to site	Accessibility to site	0,011	0,011	0,011	-0,018
Age of the building	Before1960	0,009	-0,015	-0,024	-0,024
Total Additional Cost		0,053	0,029	0,020	-0,009

Table 18: Optimizing with Undesirable Time Constraints

Factor		Net Weightage	Optimizing for age (desirable)	Optimizing for age (most-desirable)	Optimizing for assessibility (desirable)	Optimizing for assessibility (Most-desirable)	Optimizing for Quantity(desirable)	Optimizing for Quantity (Most-desirable)	Optimizing for Presence of documents(desirable)
Time Constraint	No extra time	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050
Type of connections	Wet Connections	0,047	0,047	0,047	0,047	0,047	0,047	0,047	0,047
Method of construction	Cast-in-situ	0,037	0,037	0,037	0,037	0,037	0,037	0,037	0,037
Presence of Documents	No documentation	0,019	0,019	0,019	0,019	0,019	0,019	0,019	-0,032
Quantity (no of floors)	<30%	0,014	0,014	0,014	0,014	0,014	-0,024	-0,052	-0,052
Accessibility to site	Poor	0,011	0,011	0,011	-0,018	-0,029	-0,029	-0,029	-0,029
Age of the building	Post 1980	0,009	-0,015	-0,024	-0,024	-0,024	-0,024	-0,024	-0,024
Total Additional Cost		0,188	0,163	0,154	0,125	0,115	0,077	0,048	-0,003

Conclusion: The factors affecting reuse costs can be optimized for the worst-case scenario when all the factors are undesirable. The only way to have an economically feasible case in this situation is to allow for sufficient time to balance the costs. The worst case turns economic if the buildings are from post-1980. It implies that it is mandatory to allow for time to deconstruct for prefabricated buildings when other factors are at undesirable stage. In case it is not possible to have the most desirable time constraints, then desirable time which is enough to deconstruct and find the buyer is allocated. In this condition, it is possible only when the buildings are from before 1960 and have at least medium accessibility to the site. When least desirable time constraints are posed, i.e. no extra time is allocated for deconstruction, the break-even point is attained for most desirable age, high accessibility and quantity of recoverable and at least desired level of "the presence of documents" In other words if no extra time is given, then the building should at least contain homogenous materials, have easy access to building to reduce execution time and have a good quantity of recoverable product to earn enough revenue such that it gets economically feasible. Hence a Design to Cost approach is needed for a profitable reuse case. It implies that time allocated for deconstruction should be determined based on the type of other factors which cannot be controlled. Different scenarios should be prepared for each factor and corresponding time constraints need to be determined well in advance.

6.3.2. Increase the Reuse Budget

The reuse budget can be increased by extending the reuse system boundary and taking into account the environmental impact cost. It has already been proved that the reuse of structural floor elements is beneficial for the environment (Naber, 2012), (Bleuel, 2019). Environmental costs are the cost required to compensate for the damage caused to the environment by a product throughout its life. The environmental impact of the materials used in a building is quantified in terms of environmental performance or the MPG (MillieuPrestatie Gebouw) as called in Dutch. From 2013, it was mandated by the Dutch regulation for all new constructions having an area larger than 100 m^2 to deliver MPG report at their respective municipalities. The monetary equivalent of environmental performance is called the shadow cost expressed in euros. However, these costs are not real as they are not paid by the polluters nor is there any upper limit to the MPG expressed in € per m^2 per year.

The environmental benefits of reuse are crucial as reuse diverts waste from landfill sites (Bradley, 2001). It reduces the shadow costs to about 75% (Glias, 2013) primarily because there is no extraction and manufacturing needed in reuse. The economic feasibility of reusing components will increase if the owner/polluter is made to pay for the environmental damage. However, in the existing scenario, this is not the case but in the future, it can be achieved by capping a limit to MPG and imposing fines to be paid by the polluters. Another way to implement it is to grant tax credits and insensitive for reuse equivalent to the environmental impact savings.

Calculating Environmental Impact: Life cycle assessment (LCA) is a tool extensively used for assessing the environmental impact of the buildings and its components (Bradley, 2001). In LCA, the impact is quantified in terms of emissions. The environmental categories commonly considered for building products are given in figure 39. The total impact of a product is the sum of emissions during each phase of its life cycle. In The Netherlands, Nationale Milieu Database (NMD) is a national environmental performance database of buildings, civil works, products and processes based on Life Cycle Analysis (LCA) calculations. There are tools such as SimaPro, Greencalc and EcoQuantum specially developed for these calculations (Dorsthorst & Kowalczyk, 2005). There are online calculation tools for calculating the environmental impact of the component in terms of CO_2 footprints also. For instance, the Tool Materiaal (v1.0) calculates the CO_2 profile of steel construction based on the physical and functional characteristics of the element (Staal, n.d.). For comparing the environmental impact of new components vs secondary components, the categories considered are Global Warming Potential (GWP) accounting for the emissions by the product manufacturing and Abiotic Depletion Potential (ADF) which accounts for the extraction of raw minerals and fossil fuels (Glias, 2013). Nevertheless, reuse prevents raw material extraction and product manufacturing therefore the system boundary includes the deconstruction, modification and transportation processes.

Environmental impacts commonly considered in the LCA of a building product

Depletion of abiotic resources (elements) in kg Sb equiv. and depletion of abiotic resources (fossil) in MJ

Global Warming Potential (GWP), in kg CO_2 equivalent

Eutrophication Potential (EP), in kg PO_4 equivalent

Acidification Potential (AP), in kg SO_2 equivalent

Ozone Depletion Potential (ODP), in kg CFC-11 equivalent

Photochemical Ozone Formation Potential (POFP), in kg ethylene equivalent

Figure 39: Environmental Impact Categories for Buildling Products, Source (Hradil et al., 2014)

The environmental cost of using secondary products (R_{EN}): The processes involved in the reuse also have an environmental impact, however small. Off all the processes, deconstruction (disassembly in particular) is found to contribute 90% of the Global Warming potential and Abiotic Depletion potential (Glias, 2013). The second contributing process is presumably transportation. Alexandros Glias found in his study that when the elements are transported above 500 km the impact of the reused elements is higher than that of new elements. Hence, salvaged products can be transported within a distance of 500km to keep it environmentally beneficial. He further concluded that the effect of the modification is negligible in terms of environmental impact and can only be reduced since it is a standard procedure. (Glias, 2013).

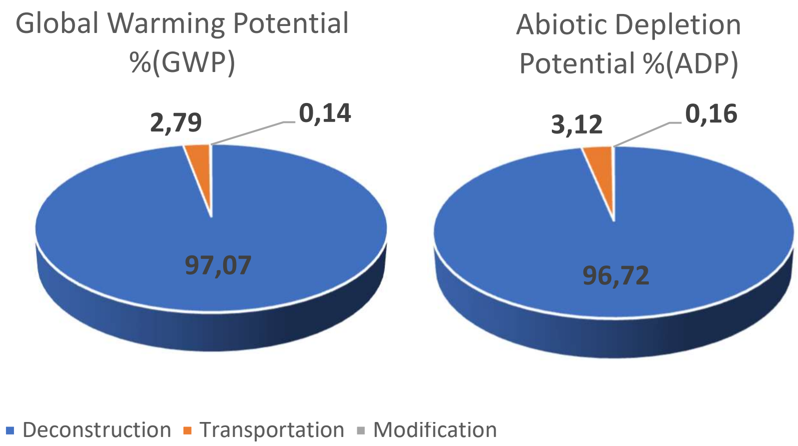


Figure 40:Environmental Impact of Reusing HCS,(Glias, 2013)

Adding the environmental cost to the system boundary will change the reuse equation as well as the tipping points equation as shown in the equation C. The effect of environmental impact costs on the tipping point will be studied in detail later in the report.

$$R_{DEC} + R_M + R_S + R_T + R_{EN} \leq C_P + C_{DEM} + C_T + C_{DIS} + C_{PR} + C_{EN} \text{ ....Eqn C}$$

7

FEASIBILITY CALCULATION TOOL (FCT)

This chapter is developed to explain the purpose of FCT, the application of this tool elaborating the method used in the tool and the detailed functioning of the tool. Thereafter the user interface is introduced. An extended discussion is also presented on the limitations and improvements that the tool can have. This chapter answers the following research sub-question:

"Q 9. What is feasibility calculation tool? How does it quantify reuse feasibility?"

7.1. Purpose of developing FCT

The tool is developed to determine if it is feasible to reuse a given component or not. It can be particularly useful for clients and owners such as a municipality, state authorities, real-estate developer or individuals who face the dilemma of reusing or demolishing. It is a predictive model which attempts to predict the future costs taking into account the variables which influence the costs. It is intended to give quantitative tipping points in terms of modification, storage and transportation type, under which reuse becomes economic. It is developed using Microsoft EXCEL program. The detailed application of the tool is described in the following section.

7.2. Application of the tool

FCT can be used as a powerful tool to calculate feasible reuse options. It has various applications for different stakeholders:

- **EOL Decision Making:** This is the central objective and application of the tool that an owner can quantitatively decide if the building should be demolished or deconstructed for component reuse. The tool gives explicit costs and levels of modification, storage and transportation for economic reuse cases.
- **Establish Demand Continuity:** The secondary material market requires a constant supply of secondary products coming from demolition stock. Feeding the data of buildings in a region to the FCT can help establish demand continuity of secondary products by building the portfolio of the existing building stock with explicit tipping points. The information on the tipping points can be very useful to match the supply with future building demands. A **visual harvest map** can be plotted with the reuse boundaries and tipping points of individual buildings. The overlapping boundaries of the buildings on the map with the future building plans can serve as a demand-supplier match.
- **Overcome time constraint:** The issue of not having enough time to find a buyer before deconstruction can be resolved by using this tool well in advance. Since the tool can virtually calculate for different scenarios, the advertisement for buyers can already begin while seeking permits or doing administrative work. Sales agreements can be made before execution through the business network or advertisements in the online market.
- **Facilitate Take Back System:** FCT enables to calculate the cost of different modification types. It is also able to give tipping points for an economic case. This information can be used to make take-back arrangements with the manufacturers who can then recover the

elements at higher precision and lower damage to make a profit from the modification budget.

7.3. Method Used

Different methods were explored through which a predictive cost model could be prepared. One of the predominant methods used in predictive cost modelling is Multiple Progression Analysis (MPR) which predicts the values based on variables. However, since the approach is based on the nature and quantification of variable, it results in greater calculation errors. The lack of comprehensive knowledge of cost variables in deconstruction and the concrete weights associated with them further made this method unsuitable for adoption. Another potential method is Case- Base Reasoning (CBR) which is used to estimate the future costs by making predictions based on existing cases. The new problems are solved based on the solutions applied to the previous one by comparing the properties of the two projects and calculating similarity percentage (Tatiya, 2016). However, this method requires a database of projects which have already been deconstructed for reuse in the past. Although, there are example projects of reuse there are hardly enough projects to analyze the type of reuse for all three scenarios (RC1, RC2 and RC3), especially for concrete floor slabs. Hence, it was also dropped after careful considerations. Another statistical method considered was Monte Carlo Simulation which is a mathematical- simulation techniques used to determine the risk and uncertainty by randomizing the selection of variables (The Economic Times, 2020). It uses inputs as probability distribution function and the results are consolidated by generating simulations (Palisade, n.d.). However, for the FCT, the assumption that the variable costs occur as probability function is not appropriate. There is a range of every variable cost component and the aim is to exploit this range and generate as big a sample of reuse possibilities as possible using these variable cost components in different combinations with one another and the fixed cost components.

Therefore, to generate various reuse possibilities, the method of **Simple Random Sampling** is found to be most befitting. For a given variable cost component, for instance, modification cost, the cost is selected randomly from the range of RM say RM3 (cost of sawing). Similarly, one cost component is randomly selected from the variable cost of storage and transportation, i.e. RS7 and RT5 respectively. This gives us RM3, RS7 and RT5 as one of the values from the variable ranges of RM, RS and RT for calculating one reuse possibility (say RC3). An example of how the reuse possibilities are generated is shown in figure 41.

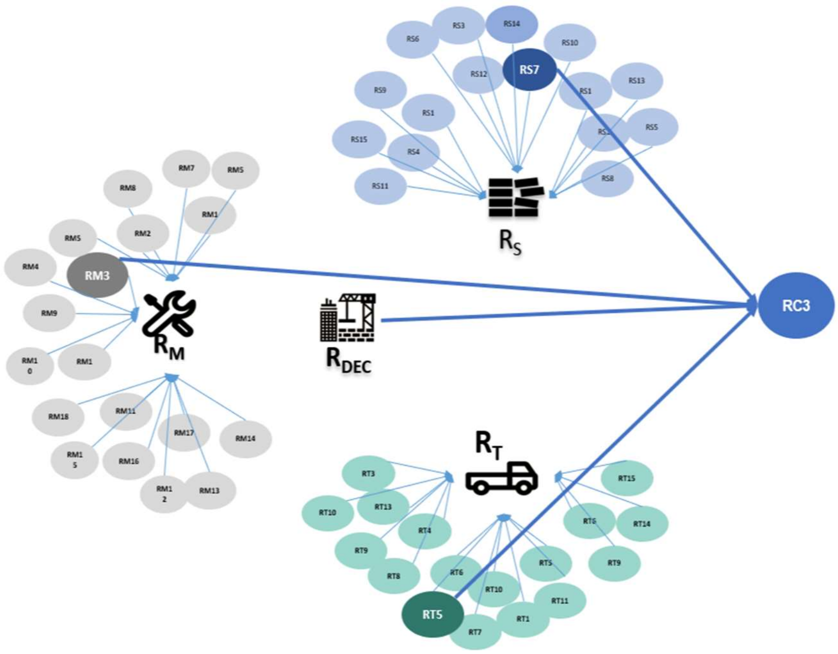


Figure 41: Concept of Simple Random Sampling, Self-Illustration

RC3: R_{DEC} (fixed cost) + RM3+ RS7 + RT5

To get a better understanding of the simple random sampling technique, 15 reuse possibilities (RC1, C2,…..RC15) are generated as shown in table 19 and figure 42. Here 15 values of Rc are generated by adding the different values of variable cost components (RM, RS and RT) to the fixed cost component (RDEC). The selection of values of variable component is carried out manually here whereas in the FCT it is automated by random sampling using the RANDBETWEEN function. The same exercise is done for 15000 times in the FCT to generate 15000 reuse possibilities by applying the RANDBETWEEN function to the variable cost components which are explained in the following section.

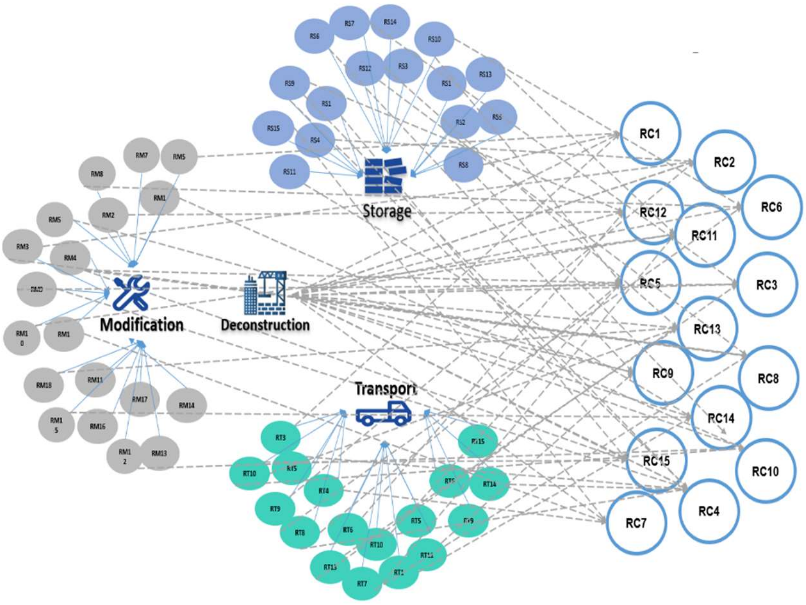


Figure 42: Example Simple Random Sampling, Self-Illustration

Table 19: Example of Manual Simple Random Sampling

R_C	=	R_{DEC}	+	R_M	+	R_S	+	R_T
RC_1	=	RDEC	+	RM2	+	RS8	+	RT14
RC_2	=	RDEC	+	RM10	+	RS5	+	RT4
RC_3	=	RDEC	+	RM3	+	RS7	+	RT5
RC_4	=	RDEC	+	RM4	+	RS1	+	RT2
RC_5	=	RDEC	+	RM5	+	RS4	+	RT11
RC_6	=	RDEC	+	RM6	+	RS3	+	RT6
RC_7	=	RDEC	+	RM1	+	RT10	+	RT1
RC_8	=	RDEC	+	RM9	+	RT14	+	RT13
RC_9	=	RDEC	+	RM13	+	RT2	+	RT10
RC_{10}	=	RDEC	+	RM15	+	RT15	+	RT3
RC_{11}	=	RDEC	+	RM11	+	RT6	+	RT9
RC_{12}	=	RDEC	+	RM7	+	RT11	+	RT15
RC_{13}	=	RDEC	+	RM1	+	RT13	+	RT7
RC_{14}	=	RDEC	+	RM12	+	RT9	+	RT12
RC_{15}	=	RDEC	+	RM8	+	RT12	+	RT8

Method Used: Generate Reuse Possibilities by Random Sampling of Variable Cost Components using RANDBETWEEN function

This is achieved by combining the fixed costs with different absolute values of the variable costs. Value of variable cost components is chosen randomly from a range. To enable this random selection of variable cost components, the RANDBETWEEN function of MICROSOFT EXCEL is used as explained below:

7.3.1. RANDBETWEEN function

A RANDBETWEEN function is a Microsoft excel function which returns a random integer between a range as specified by the user. A new random integer is returned every time the worksheet is calculated (Office, n.d.). The function works on the following syntax:

=RANDBETWEEN (bottom, top)

- Bottom= The smallest integer RANDBETWEEN will return.
- Top= The largest integer RANDBETWEEN will return.

An example of the operation of the function is shown in figure 43. To apply the RANDBEWTEEN function, one needs to assign a range consisting of lowest and the highest value of the variable cost component, as shown above, the tool then randomly selects one of these values to generate a reuse possibility, say R1. This is repeated 15000 times to get 15000 possible values of R_C. Since all the cost components in EOL cost (C_{EOL}) are fixed, the RANDBETWEEN function is applied to only Reuse Cost (R_C). Within R_C, the deconstruction cost is fixed. Hence the random sampling is applied to the modification, storage and transportation costs. Since the RANDBETWEEN works with the range, the range is to be defined for each of the variable cost components.

Formula	Description	Result
=RANDBETWEEN(1,100)	Random number between 1 and 100 (varies)	varies
=RANDBETWEEN(-1,1)	Random number between -1 and 1 (varies)	varies
	Note: When a worksheet is recalculated by entering a formula or data in a different cell, or by manually recalculating (press F9), a new random number is generated for any formula that uses the RANDBETWEEN function.	

Figure 43: RANDBETWEEN Function, source: (Office, n.d.)

- **Range of Modification Cost (R_M):** As explained earlier, the secondary component after deconstruction can be modified as per the requirement of the end-user. Each of the modification processes costs money. The range for these processes is defined as shown in figure 44. The bottom is reached when there is no modification needed to reuse the product whereas the top is reached when a combination of all types of modifications is needed at the same time i.e, sawing+ remove fixings+ filling holes+ new connection.

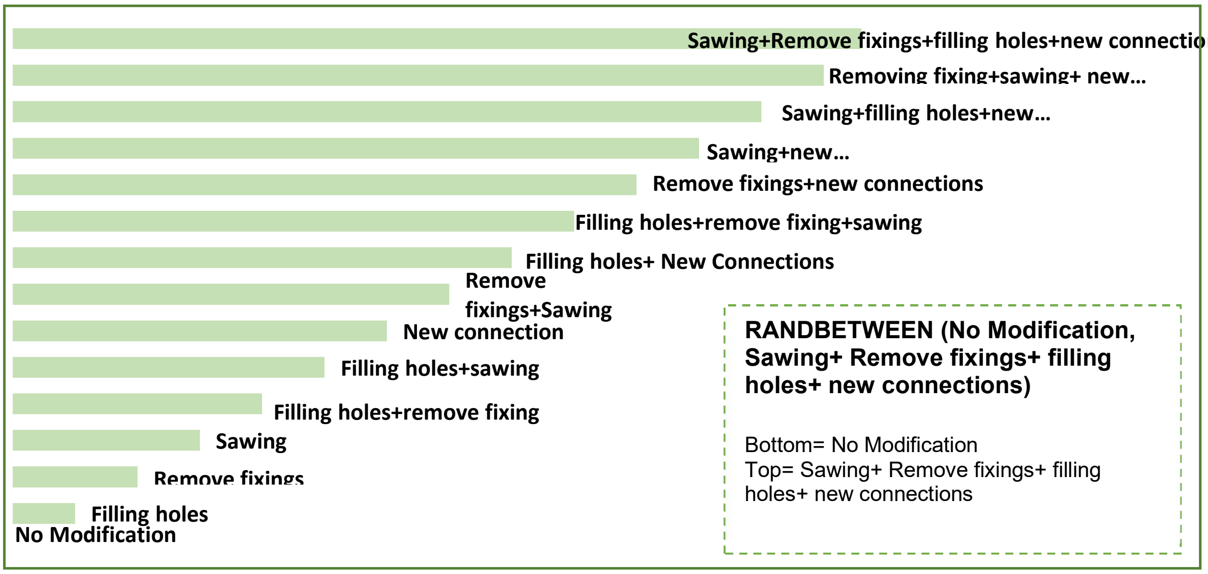


Figure 44: Range of R_M, Self-illustration

- **Range of Storage Cost (R_S):** The top and bottom of the storage depending on the type of storage which is further reflective of the reuse scenario. There is no range for RS1 and RS2 as the storage is site pilling either at the deconstruction or at the construction site which has no cost. Therefore, the top and bottom exist only for RS3, they are set in such a way that it covers futuristic possibilities as well, taking a broader range than the one found through interviews. It allows for computing the possibilities of extreme cases. For instance, for reuse scenario RS3, the bottom "3 months virtual/ at yard" and the top is "3.5

years virtual/ at yard". As learned from interviews, the components are generally stored for a maximum of one year at the yard before a buyer is found, they are then either sent for recycling or collected by waste collectors. Storage for 3.5 years is very optimistic as no owner wants to keep paying the operational costs/ rent of a yard for this long but it is kept to be the top value of the range to generate reuse possibilities if at all this kind of long term storage is needed.

- **Range of Transportation Cost (R_T):** The transportation range varies with the reuse scenario. For RS1, the components can be taken to a maximum distance of 5km whereas for RS2 (from deconstruction site to the new site) the distance can vary from 6km to 100km. Lastly, for RS3 (from deconstruction site to storage to end-user), the transportation range varies from 6km to 150km.

7.3.2. Simulations per Reuse Scenario

As mentioned before, a total of 15000 reuse cases are generated using the random sampling method. However, the distribution of these cases into the three reuse scenarios is crucial. One needs to take a realistic distribution of a number of simulations per scenario. The number of simulations for a given scenario is assumed to be a function of the distance from the deconstruction site (supply) to the construction site/end-user (demand). It implies that the chances of reuse of the secondary component increase as one moves further away from the deconstruction site. It is calculated in the following steps:

1. Assumption: For a given distance X, the number of end-users/ buildings which can consume the secondary components remains the same for every km^2.
2. If there are N number of end-users in total, the users per km^2 are given by C.
   C= N/(πx^2)
   - ➔ N= $C\pi x^2$
   - ➔ No of end-users per km= $\frac{\partial N}{\partial x} = \partial(C\pi x^2)/\partial x = 2C\pi x$
3. For a total of 15000 reuse cases, i.e. N= 15000 and a maximum distance of 150km radius around the demolition site, the value of C= 0,212. Hence the number of cases per km $(2C\pi x) = 1{,}333$
4. Using the value of C, the number of simulations per reuse scenario can be calculated as follows:
   - **Reuse Scenario 1**: it covers the reuse chances within a distance of 5km from the deconstruction site
     X= 1; no of simulations= 1
     X= 2; no of simulations=3
     X=3; no of simulations= 4
     X= 4; no of simulations= 5
     X=5; no of simulations= 7
     Total no of simulations_ RS1 = 20
   - **Reuse Scenario 2**: Similar to RS1, the simulations for RS2 are determined. RS2 covers the reuse chances within a distance of 6km to 100km
     Total no of simulations_ RS2 = 6713
   - **Reuse Scenario 3**: it covers the reuse chances within a distance of 6km to 150km
     Total no of simulations_ RS3 = 15080

Total number of simulations= RS1+ RS2+ RS3 = **21813 simulations**

It can be noted that the author initially assumed 15000 simulations, however, due to overlapping distances in RS2 and RS3, the chances are double counted as these are possible for both scenarios leading to a total of 21813 simulations.

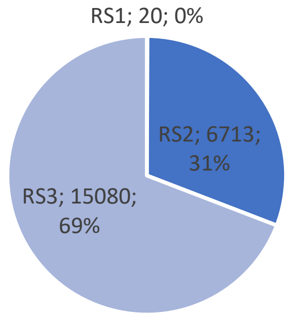


Figure 45: Simulations Per Scenario

7.4. Functioning of FCT

FCT functions in such a way that various reuse possibilities are generated and thereafter the feasible possibilities are identified for a given project. The functioning of the tool can be studied in three parts: Input; calculation and output stage. Each of these parts has different steps to be followed within as shown in figure 46.

Part 1: INPUT

In this part, the input is fed to the tool to generate results.

- **Step 00_ Formula sheet:** As a fundamental step of the tool development, a formula sheet is made. It contains all the formulas used for calculating various cost elements for the Cost of Reuse (R_C) as well as the EOL Cost (C_{EOL}). The formula sheet is made available in Appendix 3.
- **Step 01_ Fill the input sheet:** the input sheet contains the details of the project for which reuse feasibility is to be determined. It contains the fundamental characteristics of the project such as the address, gross floor area, area occupied by office space, no of floors and year of construction. Other important details include the composition of the structural floor slabs, details on the type of finishing layer, etc. An example of a filled input sheet can be found in Appendix 4.

Part 2: CALCULATION

In this part, calculations are made based on the formula sheet created in step 00 and the project inputs collected in step 01.

- **Step 02_ Cost Calculation:** In this step, the deconstruction cost (R_{DEC}) i.e. the fixed the cost element is calculated and the range of variable costs are calculated for the specific case. Thereafter, the EOL cost of the project and environmental impact cost are calculated.
- **Step 03_ Simulations per scenario**: the number of simulations per scenario are calculated in the previous section. These numbers are then used to generate reuse possibilities per reuse scenario.
- **Step 04_ Generating reuse possibilities**: In this step, the RANDBETWEEN function is applied to the variable cost component for each reuse scenario and based on the number of simulations per scenario determined in the previous step,

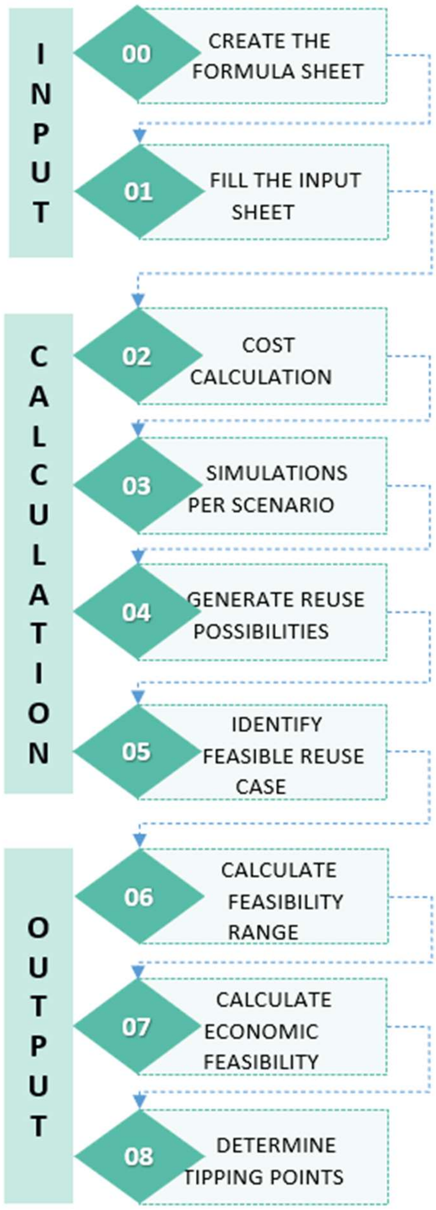


Figure 46: Functioning of FCT

reuse possibilities are created for each scenario. It is done by applying RANDBETWEEN on Modification Cost (R_M), Storage Cost (R_S) and Transportation Cost (R_T) and adding the randomly selected values to the fixed deconstruction cost to get R_C.

- **Step 05_Feasible reuse case:** Identify feasible reuse cases for each scenario by using the feasibility condition. All the reuse possibilities with each reuse scenario are individually compared with the C_{EOL}, and the ones which satisfy the feasibility condition are termed as the feasible reuse cases

$$Cost\ of\ Reuse\ (R_C)\ \leq End - of - life\ \ Cost(C_{EOL}) \ldots\ldots\ldots \text{Feasibility Condition}$$

Part 3: OUTPUT

- **Step 06_ Feasibility Range:** Calculate feasibility range for a given scenario, feasibility range is defined as the range of Rc from the lowest to the highest value for which reuse is remained feasible. The range gives an idea of the feasibility span of R_C in each scenario. The feasibility range curve is obtained by plotting the smallest, second-smallest, third-smallest, third-largest, 2nd largest and the largest values of feasible Rc for a given scenario. More values can be plotted to a smoother curve.
- **Step 07_ Economic Feasibility:** In this step, the Economic Feasibility (%) is calculated. It shows the total percentage of feasible cases out of the total reuse possibilities and also gives the percentage distribution of what per cent of feasible cases are from scenario 1,2, and 3 respectively.
- **Step 08_ Tipping Points:** This is the most important step where the actual tipping points are determined and plotted for each scenario. For RS1 and RS2, the tipping points are obtained for modification and transportation as there is only on-site storage in these scenarios. However, for RS3, there are modification, transportation, virtual storage as well as storage at yard tipping points. Along with the tipping points, the corresponding boundaries are determined as well. Another output calculated at this stage is the certification budget expressed in euros for each tipping point. The certification budget is available only when the Rc is less than the $C_{EOL,}$ i.e. for a feasible reuse case. It is calculated simply by subtracting the EOL cost from the reuse cost.

$$\text{Certification Budget= } Cost\ of\ Reuse\ (R_C) - \ End - of - life\ \ Cost(C_{EOL})$$

7.5. FCT_ User Interface

An interactive user interface is developed which allows the users to try and make different reuse choices and see for themselves if these are economic or not. The users can choose themselves different values of transportation, type of modification and storage and get an instant decision if the combination opted by them is economically feasible or not. A full image of the user interface is available in Appendix 3. The interface operates in the following steps:

STEP:01 CHOOSE TRANSPORTATION DISTANCE

In this first step, the user is prompted to choose the distance for which he wants the components to be transported. The choice can be made with a slider. The selected distance is displayed on the truck icon and also on the visual line plot

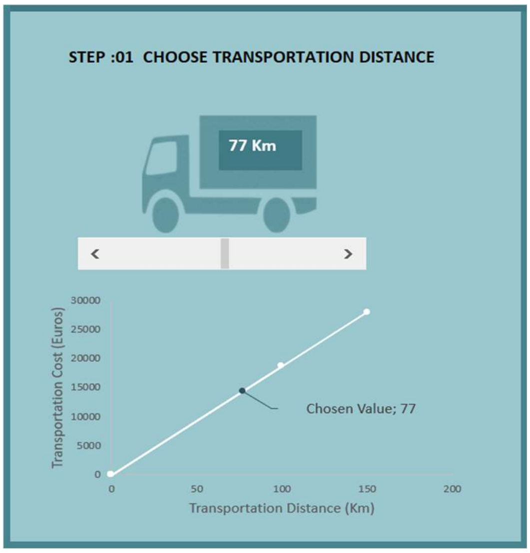


Figure 47: Step 1 _FCT user interface

below the icon. The line plot gives a visual idea of how much travel distance is selected from the range of transportation.

STEP: 02 CHOOSE TYPE OF MODIFICATION

In this step, the user gets to choose the type of modification he would like to do to the components. All types of modification combination are available on the slider to pick. The selected distance is displayed on the screen and also represented visually on the line plot below the slider. The line plot gives a visual idea of what level is modification is selected from the range of modification.

STEP: 03 CHOOSE TYPE & DURATION OF STORAGE

In this last step, the user gets to choose the type and duration of the storage he wants to store the components for. There are options available from on-site piling to virtual storage to storage at a yard. For the virtual and storage at the yard, the user can also define the duration of

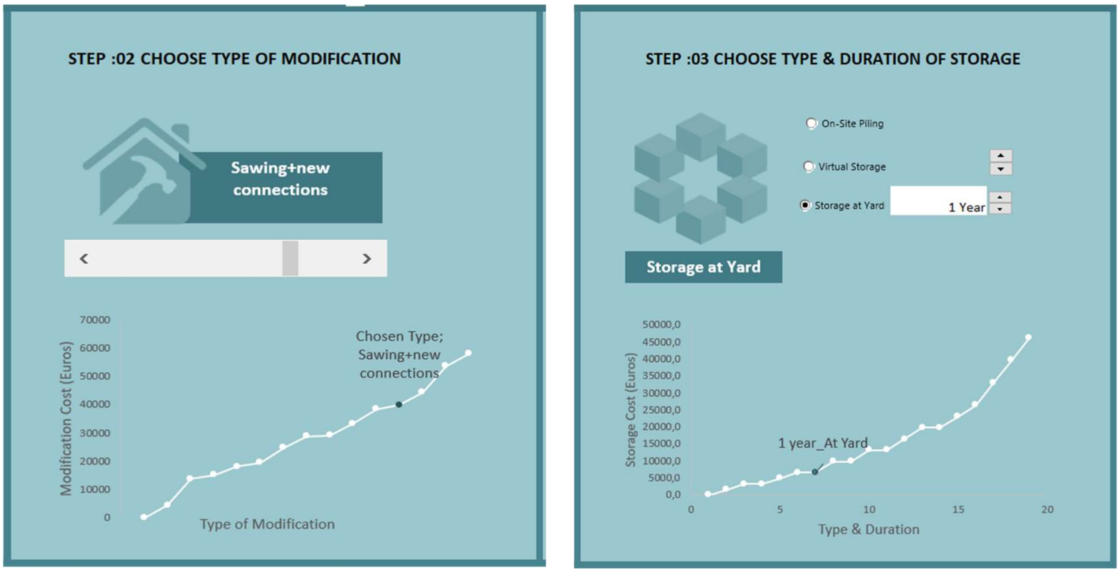


Figure 49: Step 2 _FCT user interface (Left), Step 3 _FCT user interface (Right)

storage from the list.   The selected storage is displayed on the screen and also represented visually on the line plot below the slider. The line plot gives a visual idea of where the selected value of storage stands on the range of storage.

Results: Based on the selection made by the users in step 01,02 and 03, the results are displayed on the results menu box (figure 49). It contains the reuse cost expressed in euros, i.e. for the selected type of modification, transportation and storage, how much will it cost to reuse it. The deconstruction fixed cost are automatically taken into account by the tool. The results then show the decision as to if this combination results in an economically feasible reuse case or not. For instance, for the given case, it says "Economically not feasible". At the bottom, the resulting menu also displays, under which reuse scenario is the selection made by the user-defined, is it a scenario 1 (RS1), scenario 2 (RS2) or scenario 3 (RS3) case. For instance, in the given example, the results say "RS3_Indirect Reuse". It can be verified from the selection made by the user as he chose, a transportation distance of 77km and storage at the yard for 1 year which are characteristics of RS3.

Figure 48: Results_FCT User Interface

7.6. Limitations of FCT

The current form of FCT has the following functional and conceptual limitations:

- FCT gives tipping points and reuse feasibility only for structural floor elements. It is not able to give tipping points for other components or the entire building as a whole without updating it.

- Due to the dynamic nature of FCT, random sampling technique and a large number of simulations (approx. 15000), it takes some time to rerun every time a calculation is made. Furthermore, for every other 15000 simulation set, the maximum value of Rc changes, however, small but it varies. This does not change the tipping points but the absolute value of maximum Rc.

- The cost of the new components is needed to derive the salvage value. This cost needs to be calculated from external sources (links of which are provided within FCT) and manually added to FCT.

- Currently, the environmental impact cost of the components is not calculated within FCT environment, it is instead assumed to be a fixed percentage based on the literature.

7.7. Improvements

Based on the existing set of limitations and the potential of FCT, the following improvements can be made to increase the utility and efficiency of the tool:

- Update the FCT such that it can give tipping points not only for structural floor elements but for other components and the whole building. Make necessary improvements in the formula sheet, input sheet and cost calculation sheet to incorporate data on other elements too.

- To reduce the computational time and keep the values static, build an external database of recorded simulations and feed as static data to FCT.

- Automate the cost calculation of new components within the FCT environment such that there is no need for manual entry.

- Allow for absolute calculation of shadow cost within the FCT environment.

- FCT can be used on a regional level to create harvest maps. The information on the tipping points can be very useful to match the supply with future building demands. A visual harvest map can be plotted with the reuse boundaries and tipping points of individual buildings. The overlapping boundaries of the buildings on the map with the future building plans can serve as a demand-supplier match. To achieve this, one needs to integrate the FCT with GIS to plot the coordinates and tipping points of existing stock in a region.

8

EVALUATION OF FCT

This chapter evaluates the correctness of the functioning of FCT and the results generated by the tool. The evaluation is carried out in two parts: verification and validation. Verification of the FCT allows assessing if the tool works as designed without any conceptual or operational errors. To do so, an existing office building is used as a test case to generate reuse cases and further assess feasibility. Thereafter, FCT is validated to ensure that it can produce realistic results, and prove the assertions found through literature review and interviewees. Lastly, the sensitivity of the tool is assessed by incorporating qualitative factors into the calculation and assessing if the tool can take into account the effect of these factors. The chapter concludes with the results of the evaluation of FCT. This chapter answers the last sub-question:

"Q 10. Does the tool give realistic results?"

8.1. Verification of FCT

In this section, the working of the FCT is verified with the help of a case study. The results are checked for correctness and the absolute errors percentage in the results is calculated.

8.1.1. Testing on a Case

It is important to check if the FCT contains conceptual or technical errors. To verify that simulations are programmed correctly and generate expected results, a test case building is used. It is a BREEAM certified office building currently in use, having concrete floor slab, located in The Netherlands. The building is selected such that it represents the existing building stock which needs to be deconstructed or demolished in the future. The building information is collected from BREEAM-NL and as required by the information provider, the identity of the building is not disclosed. It is referred to as Case A in the report. The following information is collected:

- **Core Attributes:** These are the project's technical characteristics which directly affect the reuse costs. It includes the building typology, building material and the component type (Dijk et al., 2000), (Philip, 2001), (Dorsthorst & Kowalczyk, 2005), (Tatiya, 2016), (Hübner et al., 2017). It is important to explicitly define these core attributes of a case before testing FCT with it.
    - Building Typology: office Building
    - Building Materials: Concrete
    - Component Type: Structural Floor Element

Referring to figure 46, the case is assessed stepwise.

- **Step 00_ Formula sheet:** The formula is sheet is made available in Appendix 3.

- **Step 01_ Fill the input sheet:** The input sheet contains the following details.

  - **Project Characteristics:** These are the fundamental characteristics of the project such as the name (not disclosed), address (not disclosed), gross floor area, area occupied by office space, no of floors and year of construction. For case A, the project characteristics are given in Appendix 4.

  - **Structural Floor Composition:** The details of the structural floor must be input into the FCT for further calculation. These details include the different types of floor components in the office: cast-in-situ/ prefabricated; physical dimensions including the length of the slab, thickness and cross-sectional details; details on the type and thickness of the finishing layer.

  The structural floor composition of case A are made available in Appendix 4

- **Step 02_ Cost Calculation:** Different cost components are calculated for the given case. First, the reuse cost calculations are made including the fixed costs (R_{DEC}) and range of variable costs. Thereafter, the EOL cost is calculated following which environmental cost are calculated. The shadow cost of the new floor component is obtained from the MPG document of the building whereas the shadow cost of reusing the secondary component is derived as 25% of the shadow cost of the new component. The detail cost calculations can be found in Appendix 4.

- **Step 03_ Simulations per scenario**: following are the number of simulations generated per scenario
  - Reuse Cases RS 1 =20 reuse chances
  - Reuse Cases RS 2 = 6713 reuse chances
  - Reuse Cases RS 3 = 15080 reuse chances

- **Step 04_ Generating reuse possibilities**: A total of 21813 reuse possibilities are generated as shown in figure 50. Along the x-axis of the plot are the number of simulations, along the y-axis are the corresponding values of Rc.

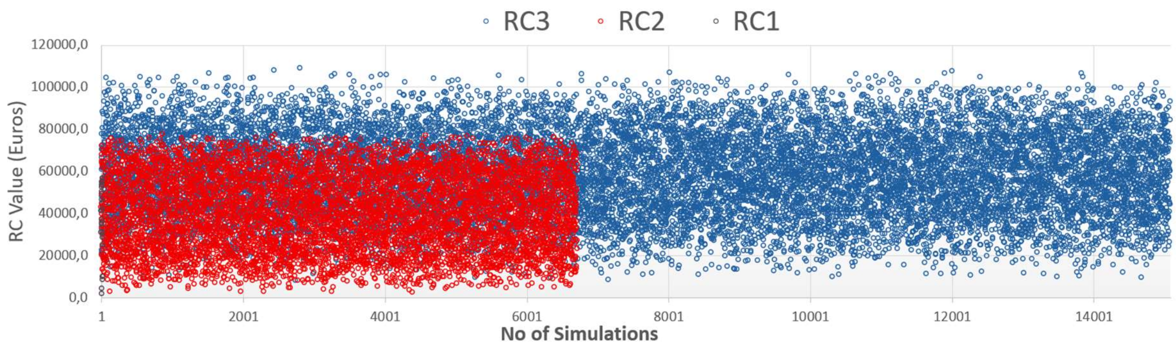


Figure 50: Reuse Possibilities

- **Step 05_Feasible reuse case:** To identify the feasible reuse cases, the Rc value of each of the cases is compared with the EOL cost. The ones satisfying the feasibility condition are identified as feasible. This is shown in figure 51. The filled points represent feasible cases while the hollow circles are the reuse possibilities initially plotted in step 04. Along the x-axis of the plot are the number of simulations, along the y-axis are the corresponding values of Rc. The demarcation line between reuse possibilities and the feasible cases can be observed at 53979,2 euros which is the EOL cost for the building.

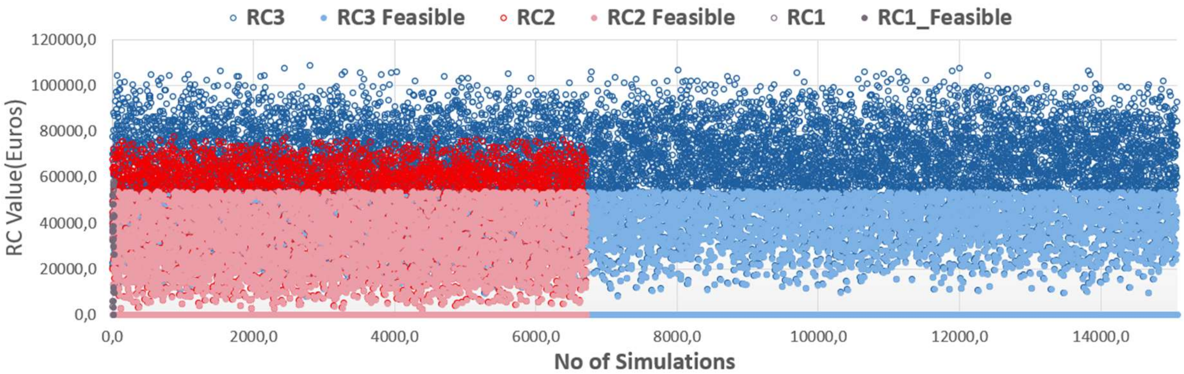


Figure 51: Feasible Reuse Cases

- **Step 06_ Feasibility Range:** As mentioned before, the feasibility range is obtained by plotting the smallest, 2nd smallest, 3rd smallest, 3rd largest, 2nd largest and the largest values of Rc. Plotting the feasibility range also provides a check as the largest value of Rc must in all cases be lesser than the EOL cost of the elements. The EOL cost for case A is 53979,2 euros.
  - The feasibility range for RS1 is shown in figure 52, it varies from 2230,7 euros to 52966,7 euros. It can be noted that the highest value of Rc is lesser than the EOL cost of the component.
  - The feasibility range for RS2 is shown in figure 53(left), it varies from 2799,7 euros to 53978,7 euros. It can be noted that the highest value of Rc is lesser than the EOL cost of the component.
  - The feasibility range for RS3 is shown in figure 53 (right), varies from 8736,7 euros to 53977,7 euros. It can be noted that the highest value of Rc is lesser than the EOL cost of the component.

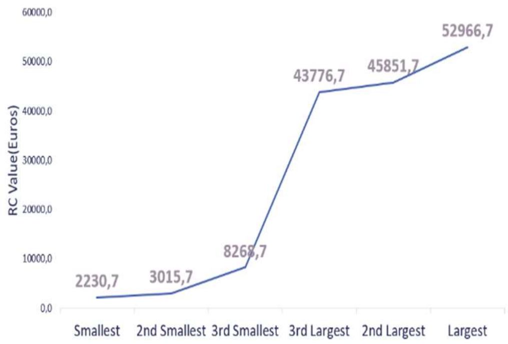


Figure 52: Feasibility Range _RS1

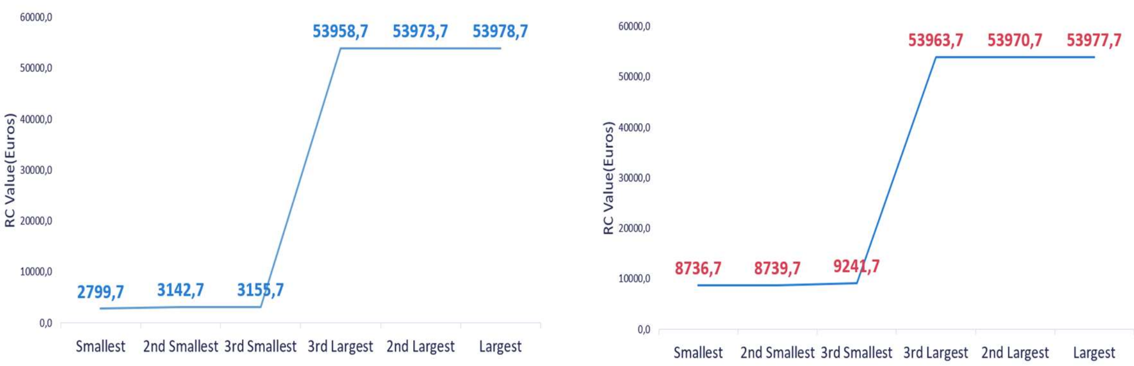


Figure 53: Feasibility Range_RS2 (left), Feasibility Range_RS3 (right)

- **Step 07_ Economic feasibility:** The Economic feasibility for case A is found to be 52,1%. It means that out of the total 21813 reuse possibilities, 52,1% of the cases are feasible reuse cases which amount to 11355 cases. Out of these cases, 29,3% of the cases are RS3; 22,6% cases belong to RS2 and 0,1% belongs to RS1. The highest certification budget for feasible cases is 9,3 euros/m^2.

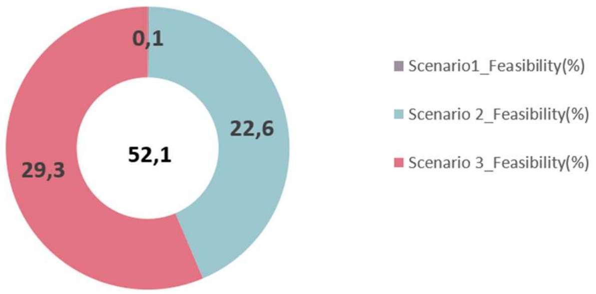


Figure 54: Economic Feasibility

Table 20: Economic Feasibility Summary

SUMMARY	
Total Cases	21813,0
%Feasibility	**52,1**
RC 1 Feasible	19,0
RC 2 Feasible	4935,0
RC 3 Feasible	6401,0
Total Feasible	11355,0
Scenario1_Feasibility(%)	0,1
Scenario 2_Feasibility(%)	22,6
Scenario 3_Feasibility(%)	29,3
No of cases with Certification	11355,0
Highest certification Budget (euro/m2)	9,3
Lowest certification Budget (euro/m2)	0,0

- **Step 08_ Tipping Points**
  For RS1 and RS2, tipping points are expressed as modification tipping points and transportation tipping points along with the corresponding boundaries. However, for RS3, there is the storage of elements as well. Therefore, the tipping points also include the virtual storage tipping points and storage at yard tipping points along with corresponding values of transportation and modification at which these tipping points are achieved. The detailed calculation of the tipping points is made available in Appendix 4. The results are as follows.

  - **RS1:** The following tipping points are observed for RS1:

    - **Transportation Tipping Point:** As shown in figure 55 (left), the transportation tipping point for RS1 is 4.9km at a corresponding modification boundary of "filling holes + new connections". It means that the secondary components obtained from case A can be transported over a maximum distance of 4.9km. The components can still be modified by filling the existing holes and making new connection points. Furthermore, this tipping value results in a certification budget of 20847.6 euros which can be spent

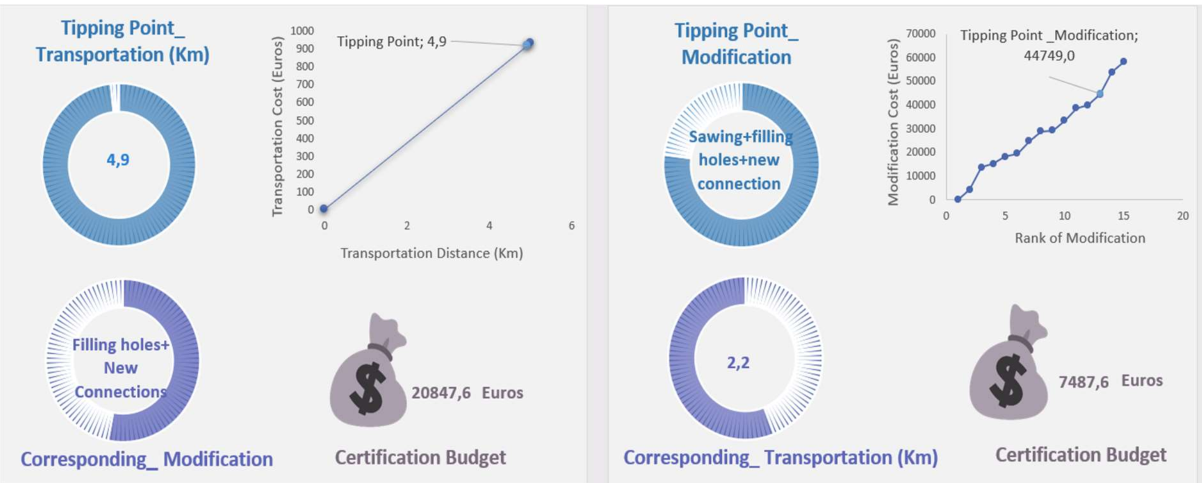


Figure 55: RS1_ Transportation(Km) Tipping Point (left), Modification Tipping Point (right)

to test the quality or certify the component.

- **Modification Tipping Point:** As shown in figure 55 (right), the modification tipping point for RS1 is "Sawing+filling holes +new connection" at a corresponding transportation boundary of "2.2km". It means that the secondary components obtained from case A can be saw to size, have the existing cutouts filled and get new connections and can then be transported for 2.2km distance. Furthermore, this tipping value results in a certification budget of 7487.6 euros.

o **RS2:** The following tipping points are observed for RS2:

- **Transportation Tipping Point:** As shown in figure 56 (left), the transportation tipping point for RS2 is 100km which is the top system boundary for RS2. However, this tipping point is achieved at a corresponding modification of "sawing" which implies that the components can be cut to size while transported to a 100km distance. Furthermore, this tipping value results in a certification budget of 17809.6 euros which can be spent to certify the component.

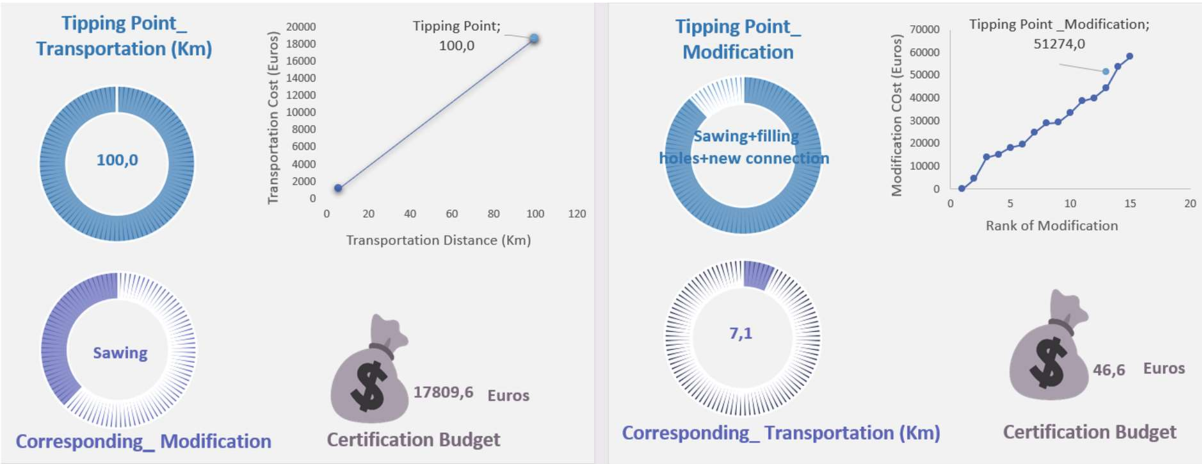


Figure 56: RS2_ Transportation (Km) Tipping Point (left), Modification Tipping Point (right)

- **Modification Tipping Point:** As shown in figure 56 (right), the modification tipping point for RS2 is "Sawing+filling holes+ new connections" at a corresponding transportation boundary of "7.1km". It means that the secondary components obtained from case A can be saw to size, the existing holes can be filled and new connections can be developed and can then be transported for 7.1 km distance. Furthermore, this tipping value results in a certification budget of 46.6 euros only, hence no money is left to invest in performance testing or certification.

o **RS3:** The following tipping points are observed for RS3

- **Transportation Tipping Point:** As shown in figure 57(left), the transportation tipping point for RS3 is 150 km which is the top system boundary for RS3. However, this tipping point is achieved at a corresponding modification of "filling holes" which implies that the existing holes in the components can be filled if they are transported to a 150km distance. Furthermore, this tipping value results in a certification budget of 14000.6 euros which can be spent to certify the component.

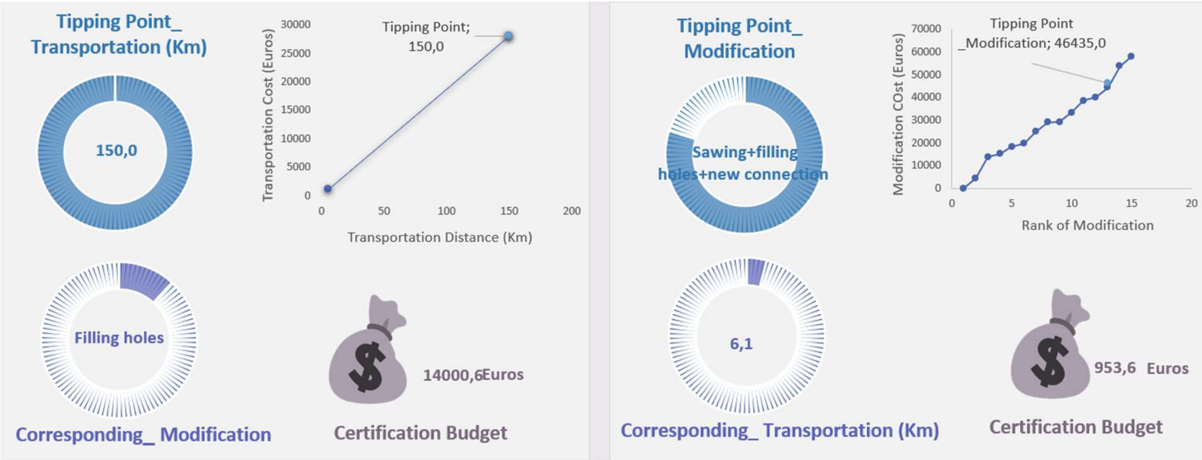


Figure 57: RS3_ Transportation (Km) Tipping Point (left), Modification Tipping Point (right)

- **Modification Tipping Point:** As shown in figure 54 (right), the modification tipping point for RS3 is "Sawing+filling holes+ new connections" at a corresponding transportation boundary of "6.1km". It means that the secondary components obtained from case A can be saw to size, the existing holes can be filled and new connections can be developed and can then be transported for 7,1 km distance. Furthermore, this tipping value results in a certification budget of 953,6 euros only.

- **Storage Tipping Point:** In RS3, there is the storage of components either virtually at the deconstruction site or after deconstruction at a yard. For case A, the tipping point for virtual storage is 21 months, i.e. the building can be left intact for this time while the owner pays the operational costs. However, the tipping point for yard storage is 42 months. Both these tipping points correspond to the modification level of "filling holes" and 8.8km transportation boundaries.

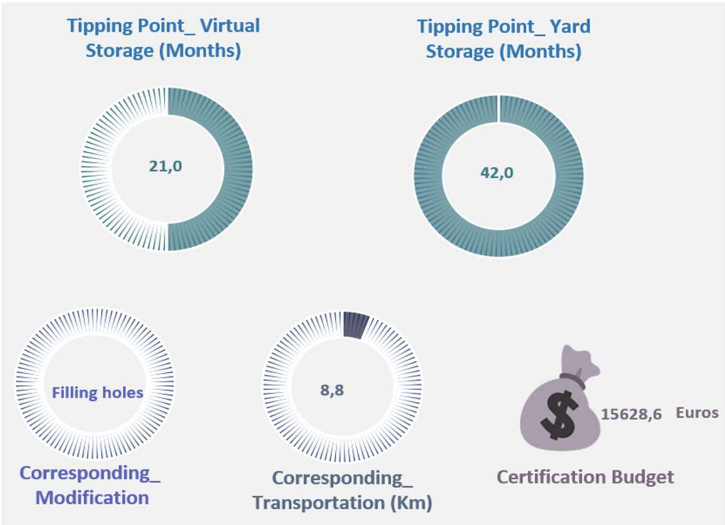


Figure 58: RS3_ StorageTipping Points

Conclusion: The FCT has been successfully tested on case A. The step-by-step functioning guide was followed. No conceptual or technical fault was observed during the application. The feasibility range, the economic feasibility (%) and the tipping points for various costs for each of the three reuse scenarios have been successfully generated by the FCT. It is interesting to note that modification costs relatively higher than transportation and storage processes. This works well for RS1 as the components can be modified to the requirements within the budget. However, the problem arises in RS2 and RS3. In these scenarios, there has to be a trade-off. For instance, the components can be modified but it implies finding a buyer within 6 and 7 km for RS3 and RS2 respectively. In practice, it is very less likely to happen. Another option is to save on the modification budget and store the element for longer duration or transport them over a long distance to find a buyer who reuses the component without any modification. It is beneficial not only from economic benefits but also environmental benefits as the process of modifying the elements has the second-highest environmental effect after deconstruction in the reuse process chain. Hence, for RS2 and RS3, the focus should be to find the right buyer with no modification requirements and store the elements or leverage the transportation budget to deliver them to far off the buyer.

8.1.2. Cost Composition

In this section, the results generated by FCT are verified if they are in line with the expected values or not. From the study of the literature and the insights gained from interviewees, it was learnt that the gross deconstruction cost is the highest. The second highest costs observed were modification costs followed by storage and transportation costs. Hence for each of the reuse scenarios, the cost components should follow the following order irrespective of which tipping point it is as the comparison is relative.

Gross deconstruction cost> Modification Cost> Storage> Transportation Cost

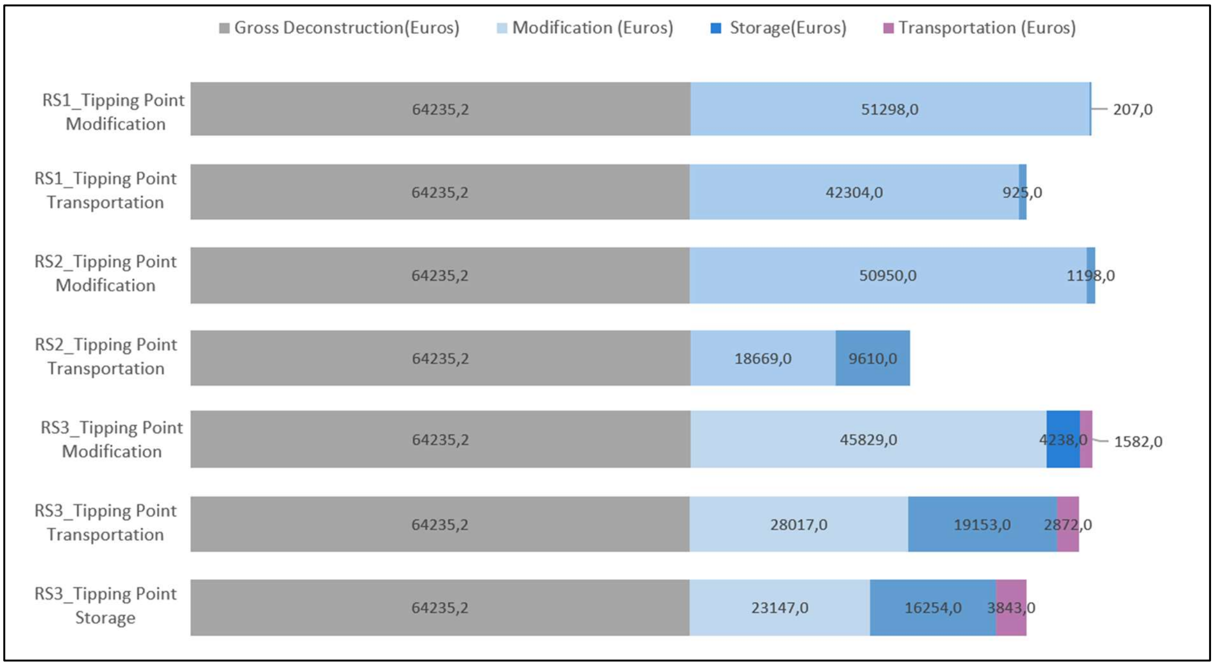


Figure 59: Cost Composition

The order of cost of various tipping points under the three-reuse scenario was evaluated to verify if the costs are in the expected order. It can be seen in figure 59, that for all of the tipping points the order of cost observed is in line with the expected cost composition: gross deconstruction cost is the highest, followed by modification, storage and the last is transportation cost.

8.1.3. Feasibility per Scenario

It is important to verify if the FCT can generate the correct feasibility within a reuse scenario. It is most feasible and economic to reuse components directly on the same site (RS1) then to transport them to another site for reuse (RS2). The least feasible option is to store the components and find a buyer for it (RS3) as the process costs of transportation and storage are higher whereas no storage is needed in other scenarios and the transportation is lesser as well. The results obtained from the FCT must reflect this order of feasibility per scenario:
Economic feasibility per scenario: **RS1>RS2>RS3**

The scenario feasibility generated by FCT is shown in figure 60. It can be seen that the tool generates the correct order of feasibility per reuse scenario.

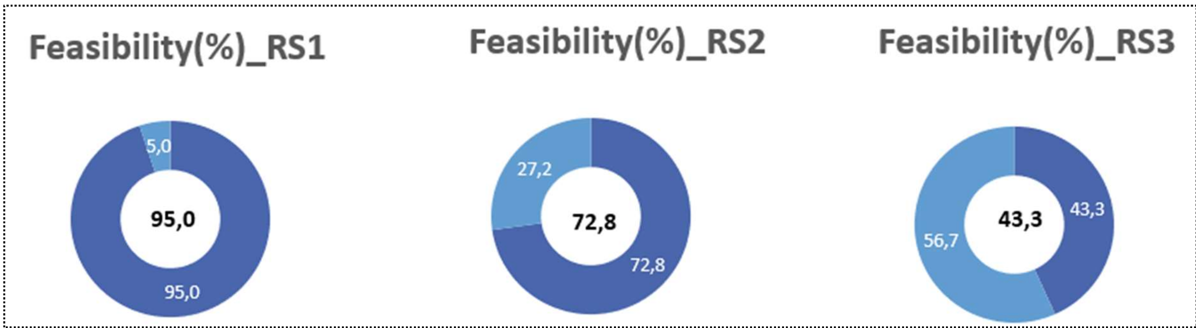


Figure 60: Feasibility per Scenario

For RS1, the total cases simulated are 20, of which 19 are feasible cases resulting in 95% feasibility for the scenario. For RS2, the total cases simulated are 6713, of which 4884 are feasible cases resulting in 72,8% feasibility for the scenario. For RS3, the total cases simulated are 15080, of which 6527 are feasible cases resulting in 43,3% feasibility for the scenario. Hence, it can be concluded that the FCT functions correctly. The results and feasibility percentages are in line with the known facts.

8.1.4. Error Calculation

As mentioned in the limitation of the tool, due to the dynamic nature of FCT, for every other 21813 simulation set, the maximum value of Rc changes, however, small but it varies. Ideally, this change in Rc must not change the tipping points because it would defeat the purpose of the tool to calculate maximum tipping boundaries if it changes every time it recalculates.

To calculate the absolute error value in the tipping points, 150 times the tool was recalculated and the tipping points obtained were recorded. After recording 80 observations, the values of the minimum and maximum tipping points under each scenario stopped changing, it implied that the maximum tipping point (expected value) has been captured to calculate the absolute error. To be sure, another set of 70 observations were further recorded, however, the maximum and minimum cease to be variable anymore. The recorded values are made available in the Appendix 4.

Absolute Error RS1: The modification tipping point varied from a max of 52526 euros to 45469 euros. The absolute error value is 7057 resulting in an absolute error percentage of -13.4%. However, when plotted against the modification tipping points, as shown in figure 61 (left), the change in values of modification does not change the modification tipping point. It remains constant at “sawing+ filling holes+ new connections”. For the transportation tipping point, it varies from a maximum value of 5km to 3.91km (figure 61_right).

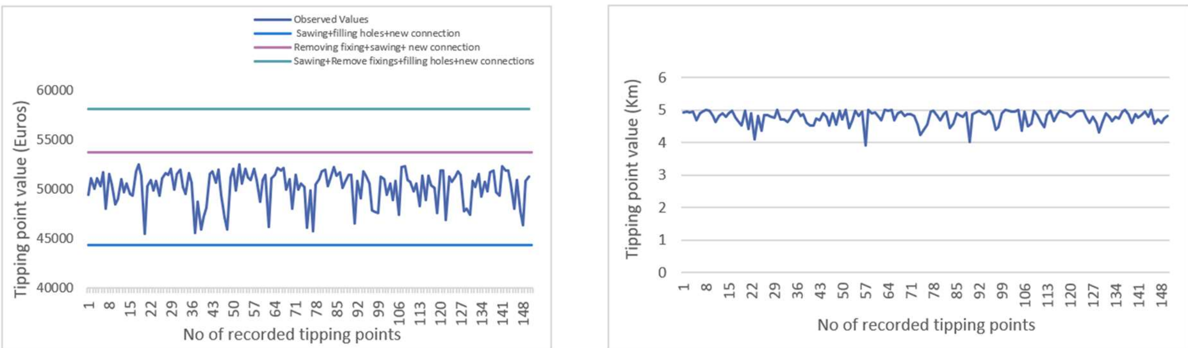


Figure 61: Error in tipping point_RS1; left(modification), right(transportation)

Absolute Error RS2:
The absolute error in RS2 is relatively much lower than RS1 because of the larger number of simulations compared to RS1. The modification tipping point varied from a max of 51498 euros to 50284 euros. The absolute error value is 1214 resulting in an absolute error percentage of -2.4%. However, when plotted against the modification tipping points, as shown in figure 62, the change in values of modification does not change the modification tipping point. It remains constant at “sawing+ filling holes+ new connections”. For the transportation tipping point, it varies from a maximum value of 100km to 98.87km, resulting in an absolute error of -0.1%.

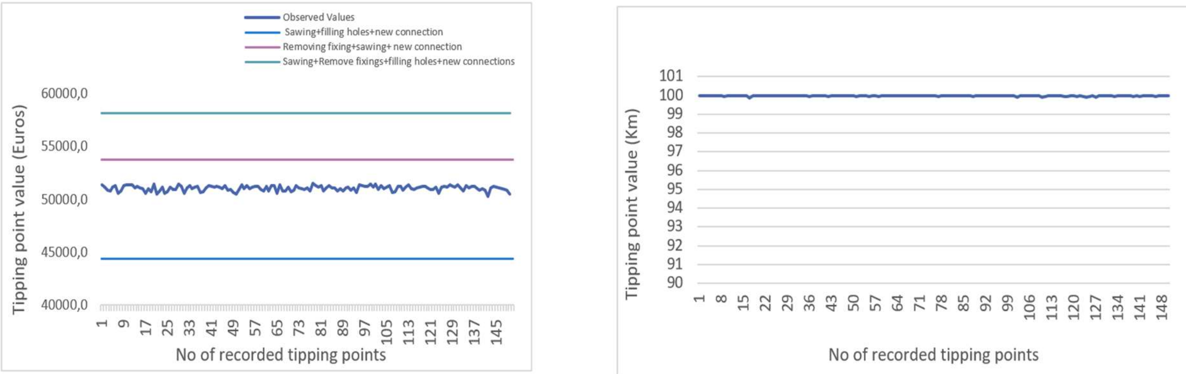


Figure 62: Error in tipping point_RS2; left(modification), right(transportation)

Absolute Error RS3:
The absolute error in RS3 is relatively much lower than RS1 because of the larger number of simulations. The modification tipping point varied from a max of 47935 euros to 44609 euros. The absolute error value is 3326 resulting in an absolute error percentage of 6.9%. However, when plotted against the modification tipping points, as shown in figure 63, the change in values of modification does not change the modification tipping point. It remains constant at “sawing+ filling holes+ new connections”. For the transportation tipping point, it varies from a maximum value of 150km to 149.75km, resulting in an absolute error of -0.2%. The error in the values of storage is -0.1% and -0.3% respectively for the virtual storage and storage at the yard (figure 64). Again this does not affect the tipping points.

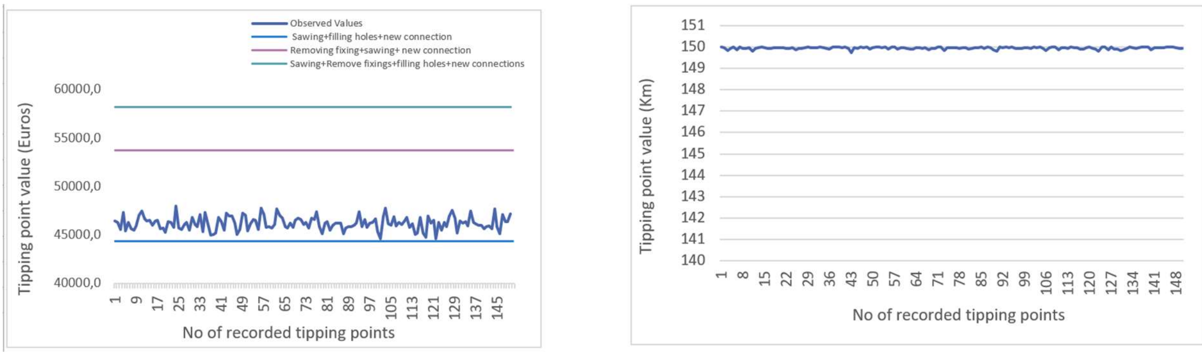


Figure 63: Error in tipping point_RS3; left(modification), right(transportation)

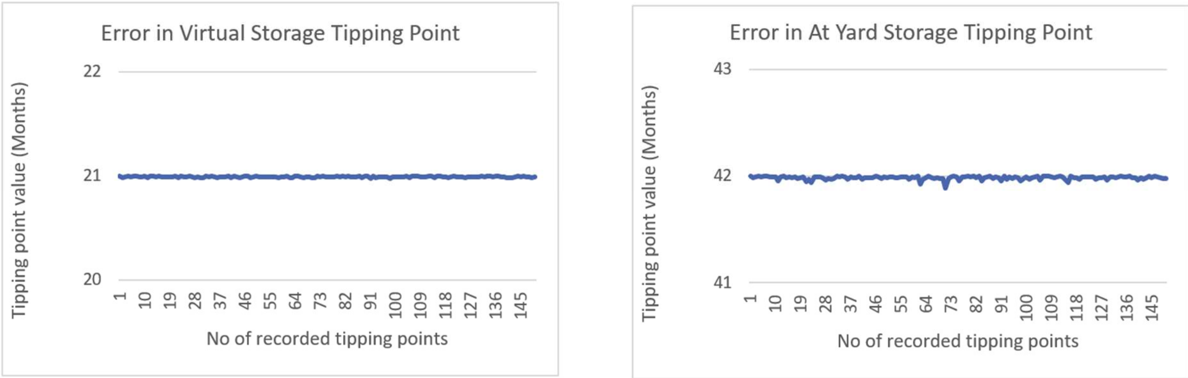


Figure 64: Error in tipping point_RS3; left(virtual storage), right(at yard storage)

Hence, it is concluded that the dynamic nature of the FCT does not affect the tipping points obtained for modification, transportation or storage for any of the three reuse scenarios. These tipping points are reliable and the absolute value corresponding to tipping points can be adjusted as summarized in table 21.

Table 21: Error Correction

Reuse Scenario	Tipping Point Type	Maximum Value	Minimum Value	Corrected Absolute value
RS1	Modification	52526,00	45469,00	Observed+13.4%
	Transportation	5	3,91	Observed+21.7%
RS2	Modification	51498,00	50284,00	Observed+2.4%
	Transportation	100,00	99,87	Observed+0,1%
RS3	Modification	47935,00	44609,00	Observed+6,9%
	Transportation	150,00	149,75	Observed+0,2%
	Virtual Storage	21,00	20,98	Observed+0,1%
	At Yard Storage	42,00	41,88	Observed+0,3%

8.2. Validation of FCT

Validation is the process followed to ensure that the conceptual simulation model is an accurate representation of the reality (Kleijnen, 1995). In other words, it is important to validate if the FCT produces realistic results. To do so, the tool is tested against the insights collected from the literature review and interviews. The following assertions are tested to validate FCT:

- **Effect of Environmental Impact Costs:** Taking the environmental impact of reusing secondary components into account can help improve the reuse feasibility and improve the tipping points for reuse case.
- **Effect of salvage value:** The reuse feasibility depends on salvage value such that the feasibility increases with when the component has higher salvage value and it decreases when the component has a low salvage value.

8.2.1. Effect of Environmental Impact

It is expected that the tipping points will improve if environmental costs are added to the system boundary of reuse cost. Alexandros Glias in his research concluded that the environmental impact cost of reusing the secondary components is 75% less than using new components. For the purpose of calculation, it assumed that the R_{EN} (environmental cost of reused materials) is 75% lesser than C_{EN} (environmental impact cost of virgin material), i.e. the shadow cost of reuse is assumed to be 25% of the shadow costs of existing floor slabs. The shadow costs of existing floor slabs are obtained from the building MPG document.

The environmental impact cost/shadow cost of the reuse process and the new product is added to the deconstruction and the CEOL cost respectively. The feasibility percentage, range and the tipping point change are as follows.

- **Effect on reuse feasibility:** The effect on reuse feasibility is studied as the number of feasible reuse cases which have increased by 31.4%. It can be seen in figure 65, that the feasibility line has moved from 53979,2 euros (C_{EOL}) to 81301,9 ($C_{EOL} + C_{EN}$).The increase in the number of feasible cases per reuse scenario can also be seen in the figure 66. Economic feasibility as a whole has increased from 52,8% to 84,2% as a result of environmental impact. Furthermore, the individual percentage for RS1 has not changed as the total number of simulation for this scenario is only 12 hence its share in the total distribution amount to only 0,1%. For RS2, the percentage of feasible cases have increased from 22,8% to 30,6% whereas for RS3 maximum increase is seen from 30% to 53,5%.

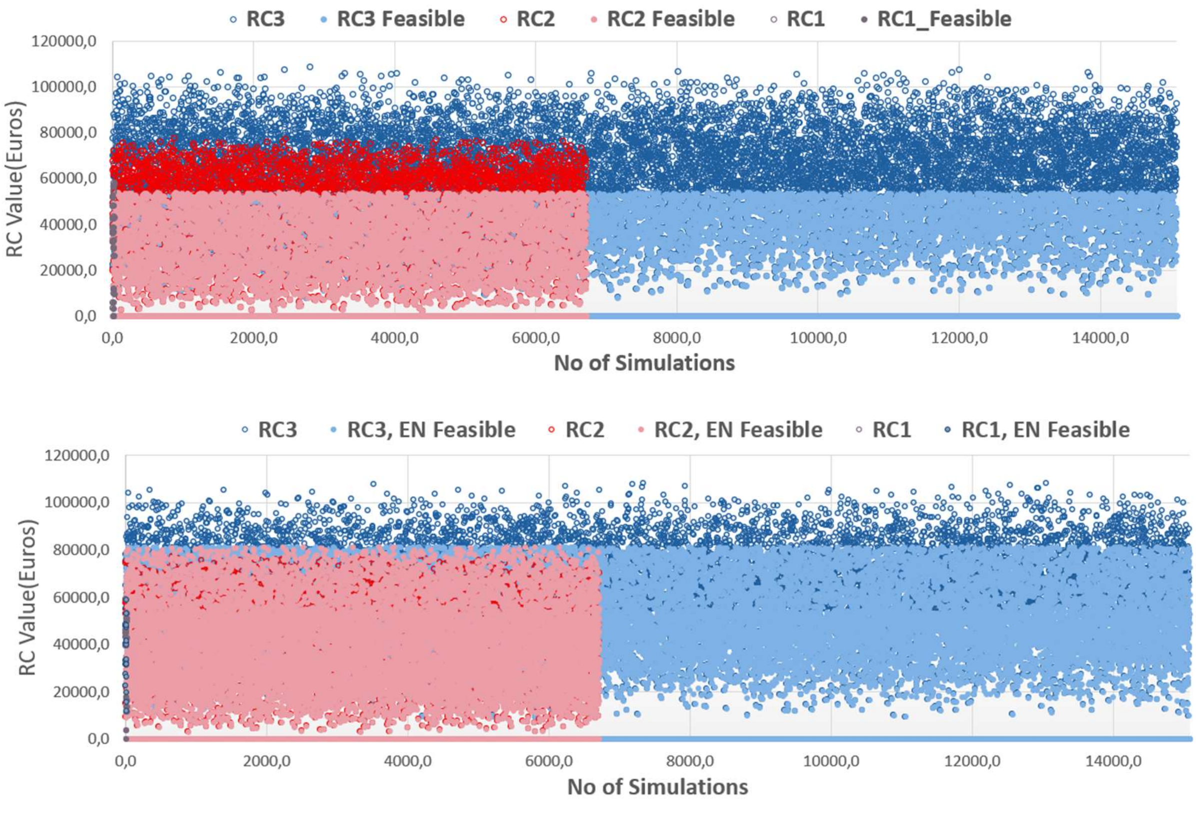


Figure 65: No of feasible reuse cases: Original(top); With Environmental impact Cost (bottom)

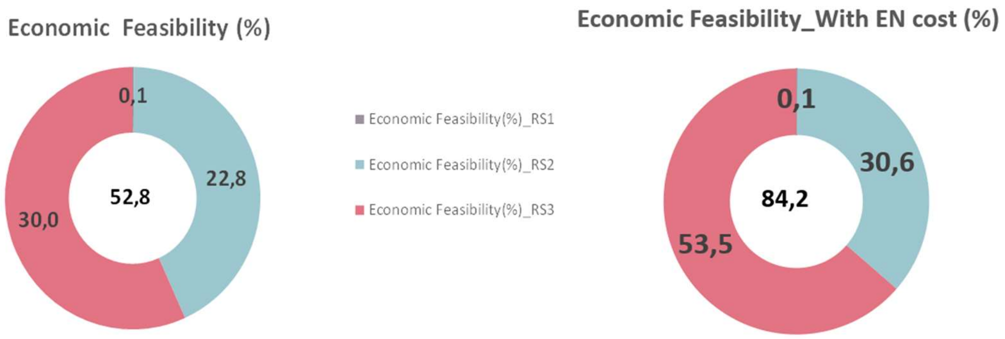


Figure 66: Economic Feasibility: Original(left); With Environmental impact Cost (right)

- **Effect on the tipping points:** The study the effect of the environmental impact cost on the tipping point, the modification tipping point is studied for the three reuse scenarios for simplicity. A similar exercise can be done for transportation tipping points as well as the corresponding boundaries.

    - **RS 1:** The effect of environmental impact cost on the modification tipping point is shown in figure 67. A significant improvement can be observed in the modification tipping values from "**Sawing + filling holes+ New Connections"** costing 48135 euros to **"Remove fixing + sawing+ new connection"** costing 54713 euros.

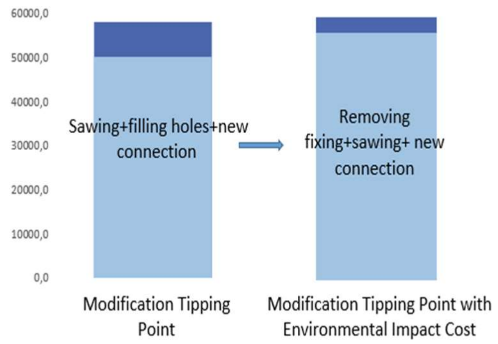


Figure 67: Effect on tipping point_RS1

    - **RS2:** Similar to RS1, the modification tipping point is improved while taking the environmental costs into account as shown in figure 68. It has changed from" **Sawing+filling holes+ new connection"** costing 50844 to "**Removing fixings+ sawing+ new connection"** costing 58126 euros. Hence, taking into account the environmental impact cost, the modification tipping point is improved by 14.3%.

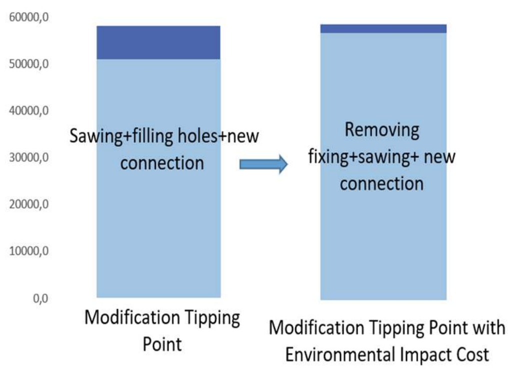


Figure 68:Effect on tipping point_RS2

    - **RS 3:** The environmental impact cost improves the modification tipping points in thiscase as well. In figure 69, the modification tipping point can be seen to change from "sawing+filling holes+ new connection" to "removing fixing+ sawing+ new connection". From the cost point of view, earlier 44731 euros could be at max spend on modification whereas now one can afford to spend 58077 euros. Hence an improvement of 29.8% in the modification tipping point.

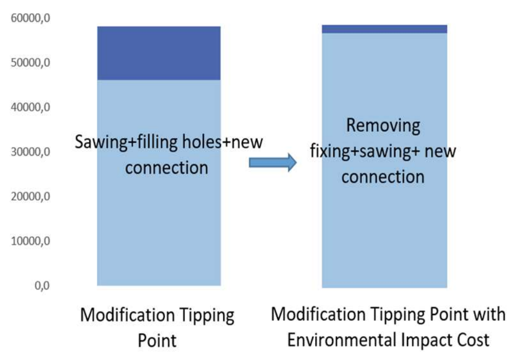


Figure 69:Effect on tipping point_RS3

Hence, it can be concluded that FCT has successfully verified the first assertion "taking the environmental impact cost of reusing secondary components into account can help improve the reuse feasibility and improve the tipping points for reuse case. "

8.2.2. Effect of salvage value

For case A, the salvage value of the components was assumed to be 40% of the value of new components based on the insights of interviews and literature review. A low-value material has a salvage value of 10-25% whereas a good quality material has a salvage of 50-85% (Bradley, 2004). To validate the FCT the following cases are simulated:

- **Effect of Low Salvage:** To simulate the effect of low salvage, the salvage value in the calculation is changed from 40% to 25% of the price of the new component. The effect can be observed in figure 70. The feasible reuse cases have reduced from 52,8% to 15,7%. As the revenue from salvage reduces from 62904 euros to 39314,7 euros, the net deconstruction cost increases from 1331,7 euros to 204920,7. Therefore it can be seen in figure 68 that the minimum Rc is above 204920 euros. However, the minimum feasible Rc

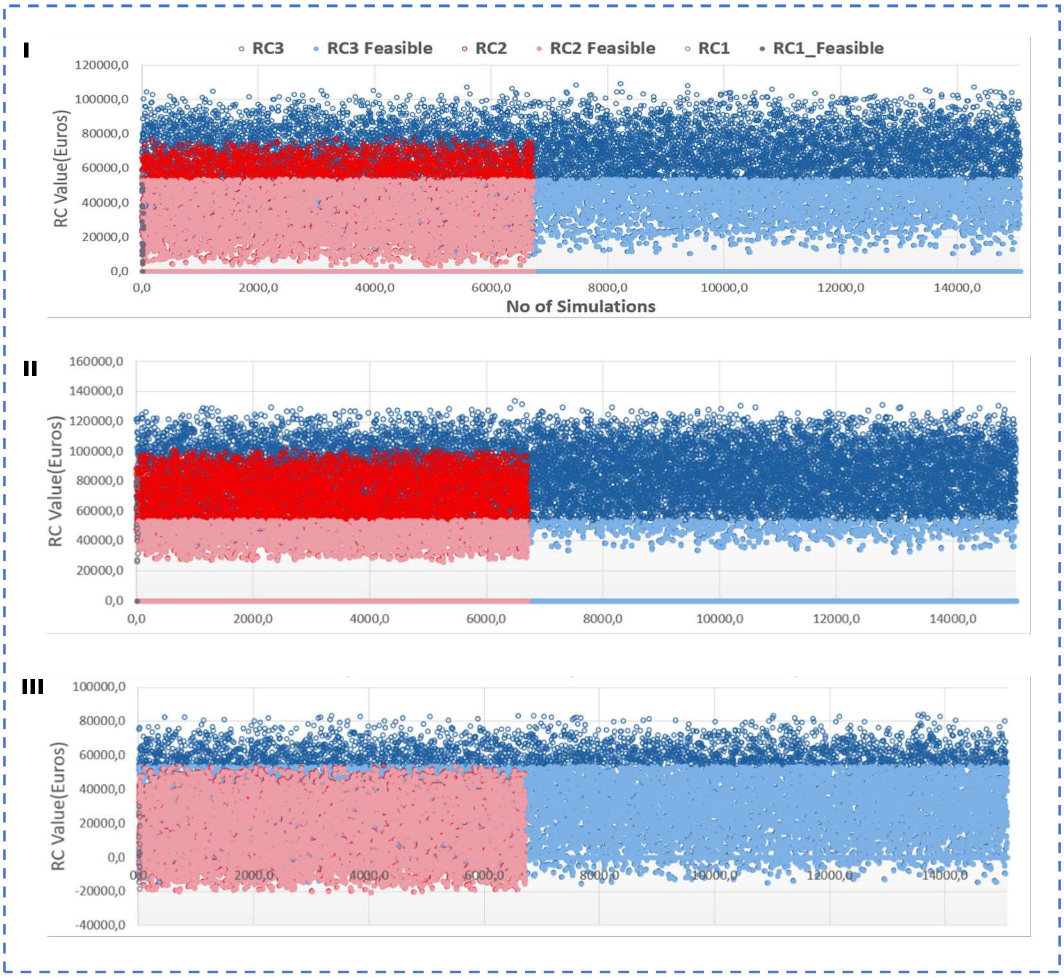


Figure 70: Effect of Salvage value, I= Original Case;II=Low Salvage Case; III= High Salvage Case

is as low as 1331,7 euros because, with a salvage revenue of 40%, the net deconstruction costs is 1331,7 euros.

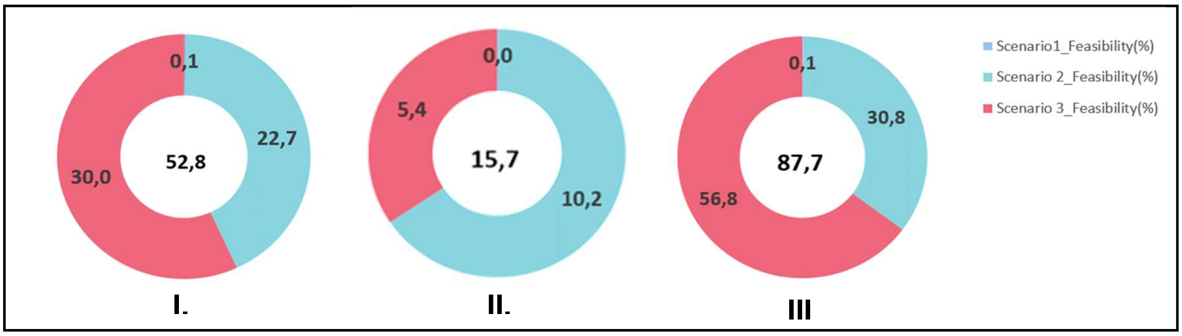


Figure 71: Effect of Salvage value on Economic feasibility (%), I= Original Case;II=Low Salvage Case; III= High Salvage Case

- **Effect of High Salvage:** To simulate the effect of high salvage, the salvage value in the calculation is changed from 40% to 55% of the price of the new component. As the revenue from salvage increases from 62904 euros to 86492,3 euros. As a result, the deconstruction cost is reduced from 1331, 7 euros to -22257,2 euros, i.e, a net profit. the net deconstruction cost decreases. Furthermore, the Economic feasibility (%) has increased from 52,8% to 87,7% as shown in figure 71. An interesting observation to make here is that the effect of high salvage (87,7%) on the Economic feasibility is comparable to the effect of environmental impact (84,3%) cost on Economic feasibility.

- **Effect of Salvage on the tipping point:** The effect of salvage on the modification tipping points of RS1, RS2 and RS3 are shown in figure 72,73 and 74 respectively. Comparing I. to II. in the figures, the modification tipping point has reduced in each of the three reuse scenarios as the fixed cost of deconstruction has increased by reducing the revenue from salvage. Comparing I. to III., the modification tipping point has increased in each of the three reuse scenarios as the fixed cost of deconstruction has decreased by increasing the revenue from salvage.

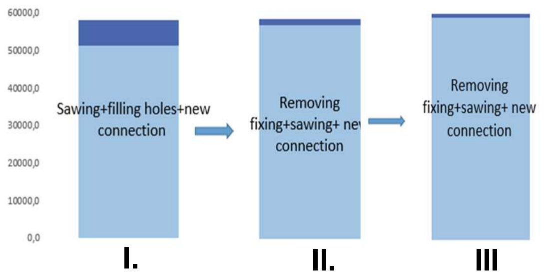


Figure 72: Effect of salvage value on modification tipping point_RS1: I= Original Case;II=Low Salvage Case; III= High Salvage Case

Hence the Economic feasibility increases with higher salvage value and decreases with lower salvage value. Furthermore, the tipping points increase with higher salvage value as higher budget is available whereas the tipping points are reduced if the salvage is low as it results in high deconstruction costs. Therefore, it can be concluded that the FCT can prove the second assertion" The reuse feasibility depends on salvage value such that the feasibility increases with when

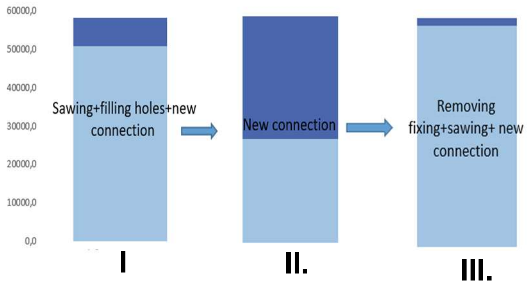


Figure 73:Effect of salvage value on modification tipping point_RS2: I= Original Case;II=Low Salvage Case; III= High Salvage Case

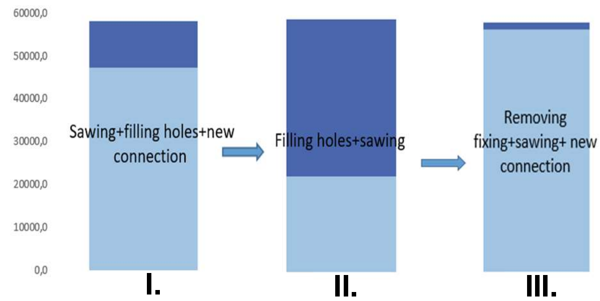


Figure 74:Effect of salvage value on modification tipping point_RS3: I= Original Case;II=Low Salvage Case; III= High Salvage Case

the component has higher salvage value and it decreases when the component has a low salvage value".

8.3. Sensitivity Analysis

Sensitivity analysis is carried out to determine if the model's behaviour is following the judgements of the experts (Kleijnen, 1995). The experts used in this study identified and weighted the "factors affecting reuse cost". Therefore, to assess the sensitivity of FCT, qualitative factors affecting the reuse cost are used. The impact of each of these factors has been established with AHP analysis and interviews with the stakeholders. If FCT can generate the same impact known previously, the tool is rendered to be sensitive for application. The sensitivity is assessed for three most influential factors namely, the time constraints, type of connections and method of construction as they constitute the majority of the total impact on the reuse cost (71.4%). To do so, the effect of factors is calculated for scenario 1, it can be similarly calculated for scenario 2 and 3 as well.

To prove: Applying the most-desirable conditions of the factors affecting the reuse cost results in cost savings as a result of which the net budget increases. The FCT must be able to show this increase in the budget as an improvement of the tipping point and the corresponding variable cost.

Method Used: A function cost analysis is performed using cost tables. A cost table contains a multi-dimensional database with several attributes of one or more functions(Dean, n.d.). The effect of changing these attributes can be seen by the cost table which estimates the cost of the improved function. For the given case, the cost table contains different transportation costs and modification costs possible within RS1. Here the function is the total cost of reuse (calculated as the sum of transportation, modification and deconstruction cost) and the attributes are the factors affecting this cost. Having applied one of the attributes the resultant reuse cost changes which can be spotted from the cost table. A detailed step-by-step explanation of the calculation is provided in Appendix 4.

8.3.1. Time Constraint (Most-Desirable)

It was found to be the most influential factor affecting the reuse cost. It is expected that in case of most-desirable condition where there is no time constraint and it is at the discretion of the contractor, the costs saved should increase the budget and thereby improve the tipping points and the corresponding variable cost. One can expect a greater improvement in the corresponding cost than in tipping point as tipping points are already close to the top boundary of their respective systems.

1. Effect of Time Constraint on Tipping Point _Modification

As shown in figure 75, under most-desirable conditions of time constraints (i.e. when there is no time constraint), the cost savings increase the reuse budget which then improves the tipping point of modification from **" Sawing+ filling holes+ new connection"** costing **50315,0 euros** to **"Removing fixing + sawing + new connection"** costing **57382,2 euros.** Hence, the tipping point for modification is improved by 14% under most-desirable conditions of time constraint. As shown in figure 75, under most-desirable conditions of time constraints (i.e. when there is no time constraint), the cost savings increase the reuse budget which then improves the transportation corresponding to the modification tipping point from **" 3.8 Km"** to **"5km".** One can observe comparatively higher improvement in corresponding transportation than in the modification tipping point itself.

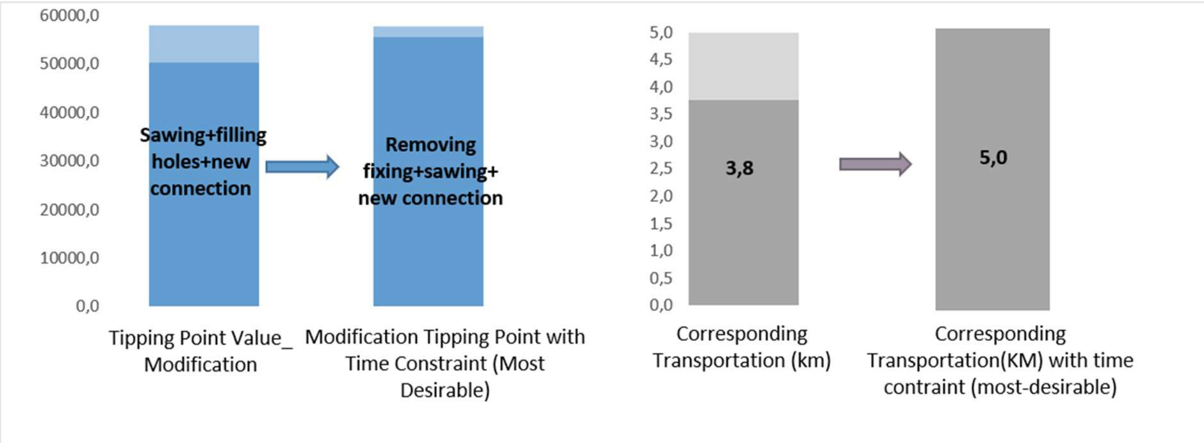


Figure 75: Effect of Time Constraint on Tipping Point _Modification

2. Effect of Time Constraint on Tipping Point _Transportation

In this case, the tipping point is improved from **" 4.9 Km"** to **"5km"** which is the maximum transportation system boundary for RS1**.** The improvement is less since the tipping point was already very close to the maximum. The modification corresponding to transportation tipping point has improved from **" Filling Holes"** costing 8297,0 euros to **"Sawing"** costing 15417,6 euros, a net improvement of 86%.

Figure 76: Effect of Time Constraint on Tipping Point _Transportation

8.3.2. Type of Connection (Most-Desirable)

1. Effect of Type of Connection on Tipping Point _Modification

With the most desirable type of connections (Dry+ Demountable), the cost savings improve the modification budget from **50795,0 euros** (**Sawing+ filling holes+ new connections**) to **57404,0 euros** (**Removing fixing+ sawing+ new connection**) increasing the modification tipping point by 13% (figure77). The effect on the corresponding value of transportation is shown on the right side in figure 77. The transportation distance with most desirable connection improves from **4km to 5km** (20% improvement).

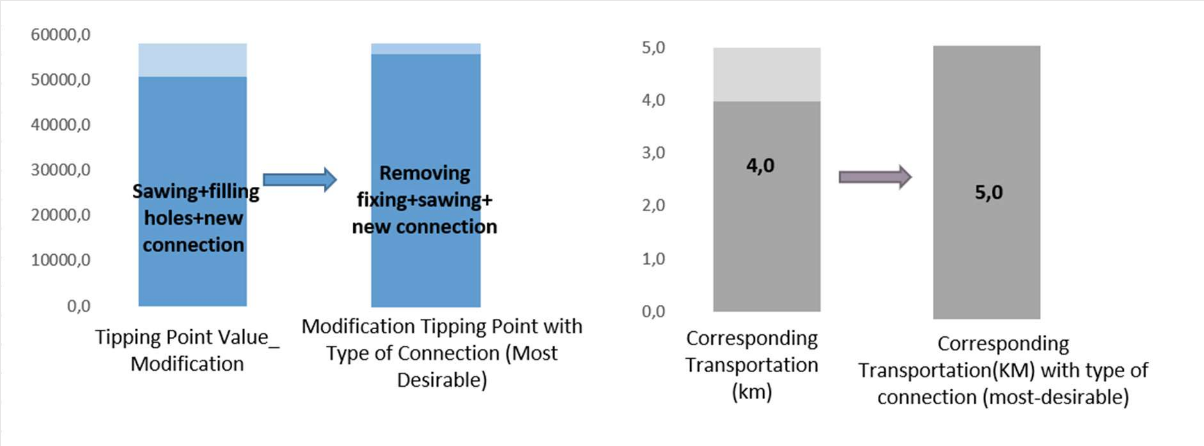


Figure 77: Effect of Type of Connection on Tipping Point _Modification

2. Effect of Type of Connection on Tipping Point _Transportation

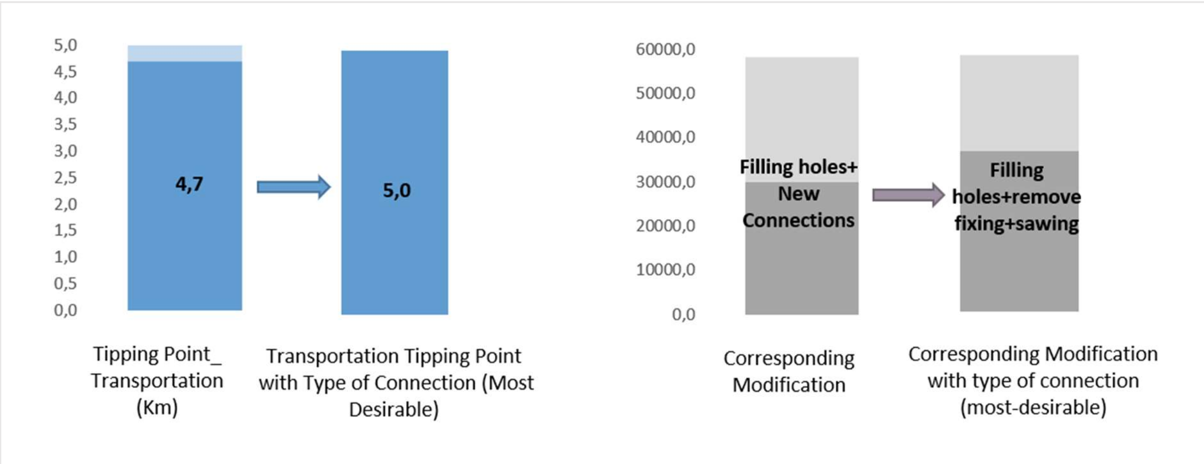


*Figure 78:*Effect of Type of Connection on Tipping Point _Transportation

The tipping point for transportation is improved from 4.7km to 5km (6.4% improvement) as a result of the most desirable type of connections. As expected, the improvement in the corresponding value of modification is substantial. From **"Filling holes+ New Connection"** costing 29973,0 euros, the budget is increased to **"Filling holes+ remove fixing+ sawing"** costing 36428,3 euros resulting in an increment of 21.5%.

8.3.3. Type of Construction (Most-Desirable)

1. Effect of Type of Construction on Tipping Point _Modification

The tipping point of modification improves from **"Sawing+ filing holes+ new connections"** to **"Removing fixings+ sawing+ new connection"** with the most-desirable type of construction i.e. prefabricate construction which is designed for disassembly (figure 79). The budget, in this case, improves from 51732,0 euros to 56942,7 euros (10%). Greater improvement is observed in the corresponding value of transportation, increasing from 4km to 5km.

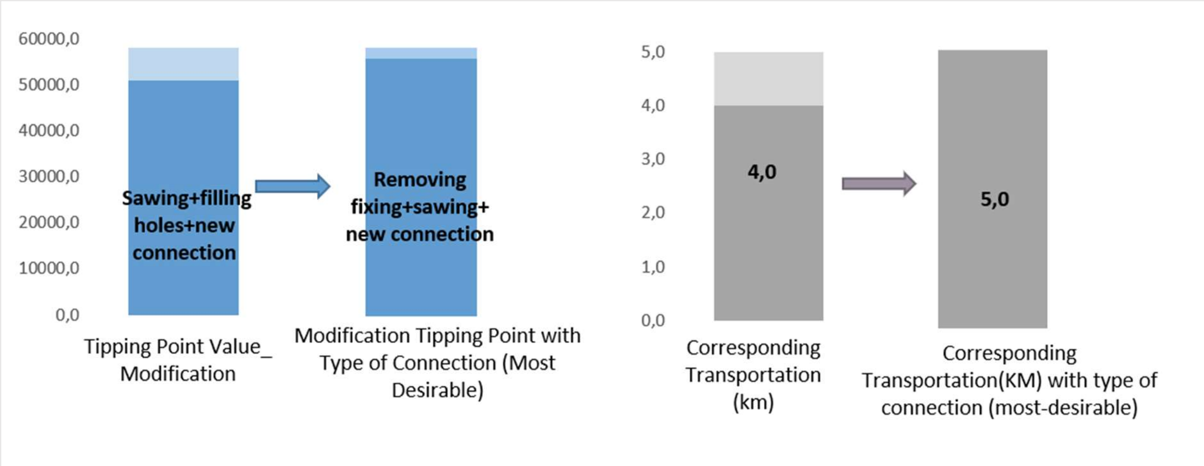


Figure 79: Effect of Type of Construction on Tipping Point _Modification

2. Effect of Type of Construction on Tipping Point _Transportation

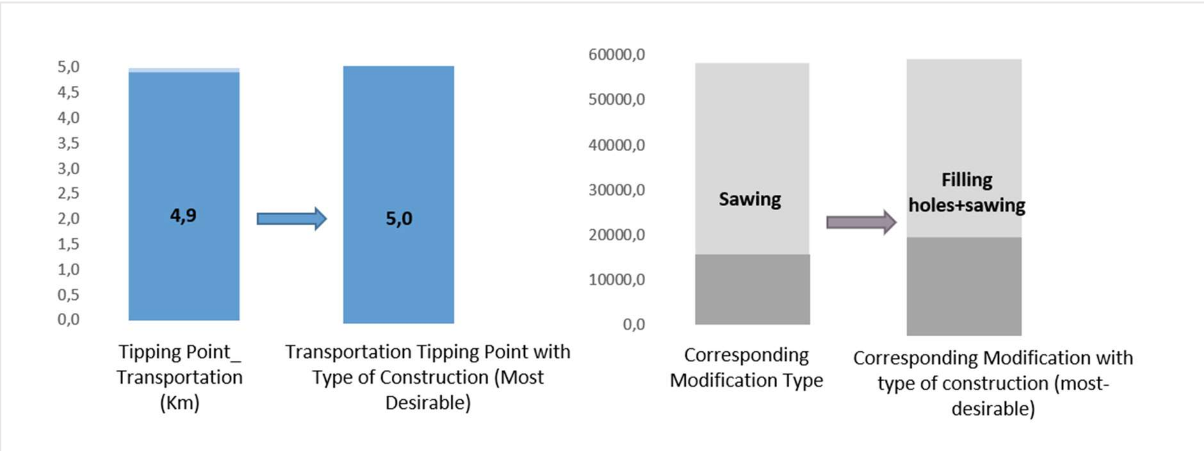


Figure 80: Effect of Type of Construction on Tipping Point _Transportation

For the most-desirable type of construction, the tipping point for transportation increases from 4.9km to 5km whereas the corresponding modification budget which was earlier limited to 15604,0 euros enabling “sawing” of the element increases to 20796,6 euros allowing for “filling holes+ sawing” (figure 80).

8.3.4. Results

The results of the sensitivity analysis are tabulated in table 22. It can be observed that the application of most-desirable conditions of the factors has resulted in improved tipping as well as corresponding cost components as well. This proves the first hypothesis of the analysis. Furthermore, one can observe that the increase in the corresponding cost element is substantially higher in each of the cases than it is for the tipping point itself. Hence, the second hypothesis is also proved.

Table 22: Results_Sensitivity Analysis

Factor	Increase in Tipping Point_ Modification (%)	Increase in Corresponding Transportation (%)	Increase in Tipping Point_ Transportation (%)	Increase in Corresponding Modification (%)
Time Constraint	14%	31.57%	2%	86%
Type of Connection	13%	20%	6,4%	21,5%
Type of Construction	10%	20%	2%	33,2%

Therefore, it can be concluded that the FCT is sensitive enough to indicate the effect of factors affecting the reuse costs in real life in terms of improved reuse budget and tipping points. Hence, sensitivity analysis is successful.

9

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions and recommendations of the research. The conclusions are provided as answers to the research questions formulated in Chapter 2, the main findings of the research are highlighted as well. The recommendations comprise of the actions for stakeholders and suggestions for further research to realize structural component reuse in an economically feasible way.

9.1. Conclusion

The answer to the main research question: ***"How to quantitatively assess the economic feasibility of reusing structural components from existing buildings into new construction?"*** *is the* **Feasibility Calculation Tool***.*

This research has resulted in the development of the Feasibility Calculation Tool (FCT) which can be used to quantitatively assess the economic feasibility of reusing structural floor elements. The tool provides different reuse options and explicitly shows the tipping points in terms of variable costs (modification, transportation and storage) beyond which reuse is not economically profitable. Thus, the FCT can be successfully used for a circular EOL treatment. The reuse scenario and the tipping points for the structural floor elements can be evaluated well in advance before the building reaches EOL, guiding the decision of the owners to demolish or deconstruct for reuse. A well-planned deconstruction can further help find buyers in time and deconstruct with higher precision as per the requirements of the buyers increasing the salvage cost and decreasing the need to modify components after deconstruction.

Q1. What is the state- of- art concerning structural component reuse?
The building industry is traditional in the EOL treatment of the building. The structure is crushed down into mixed debris and recycling is the highest level of waste management adopted in the sector. It is the usual business to recover non-structural elements such as partition walls, floor tiles, doors, windows, furniture and roof tiles for sale. Rest everything is sent for recycling. Concrete is reused only on material level in new concrete and not on component level. The structural components if recovered are reused for non-structural purposes. For example, in cast-in-situ concrete, huge blocks are cut out and reused for pavement for the new site but it is not being reused as a structural component. The only material deconstructed to be reused for structural reuse is the metal construction frame, steel structure.

The best practice is to investigate the building from top to bottom and aim for highest value recovery following the 7R model, to see if the building can be reused as a whole or take apart the components for reuse or the least reuse at the material level. The last option to adopt should be demolition.

Q2. Why is reuse uneconomic? What are the underlying challenges of structural component reuse?

Deconstruction for reuse is more expensive than demolition because it is a time-consuming process and requires skilled labour. The demand inconsistency is high as there are no established markets for secondary components to sell and procure from. Currently, the contractors do not store the elements and deconstruct only when there is a buyer in place. Another reason for demand inconsistency is the lack of information on the availability and properties of secondary materials. There is no database for existing building stock. The more established market for recycling and cheaper cost of new materials also add to the economic challenges. Furthermore, there are technical challenges such as lack of knowledge of deconstruction and skilled labour. Other processes such as efficient site logistics, cataloguing and testing for quality are fairly unknown as well. Old buildings are seldom documented and the ones which have some drawings are often not updated leading to design inconsistency. Hence, the contractor needs to investigate what's inside the building himself and test for the strength and durability of it. Furthermore, there is no method of certification of the secondary components. Re-certification of the components in most of the cases is not possible. No policies or binding laws are stipulating structural component reuse or reuse for that matter.

To facilitate reuse and understand the reuses costs better, it should be supported by concrete policies. However, to ensure demand continuity, it is needed to back up stock to feed the construction demands. Therefore, central storage facilities are needed. A centralized database should be created to match the demand of new building with existing stock, hence reducing the demand inconsistency and eventually the cost of procurement by procuring from closer buyers. To overcome the hardship posed by extra time invested in deconstruction, Guy Brandley in his research proposes to have a shorter delay ordinance for deconstruction against standard ordinance period for demolition. Another way to deal with this is to provide for a mandatory waiting period between the granting of the demolition permit and the commencement of new construction to allow enough time (Bradley, 2001). Advertising the components for sale is also important to avoid the risk of not finding a potential user. It can be done at an online market place or via a network of businesses. Advertising the components before demolition can help reduce the risks and cost of storage of the products (Michael, 2018) by finding the nearest buyer.

Q3. What is the process to deconstruct a building for reusing components? How does it vary from traditional demolition practice?

Demolition is a simple and quick process to turn down the building and clear the site for the new project. It requires a maximum of two workers whereas deconstruction for reuse is a labour-intensive process. Apart from creating unsorted debris, demolition leads to health hazards such as dust production, noise pollution from the machine, etc.

Deconstruction, on the other hand, is a much more complex process, involving the deconstruction stage, material handling stage and the consumption stage. It begins with obtaining the permit, doing the site audit, making detail inventory of the components, drafting the deconstruction and waste management plan, advertising to find buyers, preparing the site and recovering the components from temporary layers of the building i.e. soft-stripping. Thereafter the actual execution or the disassembly process starts with the performance testing of the components. The level of testing depends on the presence of documents and the requirement of the user. There is no performance protocol, second-party conformity tests are done when the end-user wants to tests for the quality. Thereafter support systems are erected after which the top finishing layer of concrete is removed to reach to the joint. The connections are then sawed and the slabs are lifted off. Then, starts the material handling stage. The first step in the material handling process is to modify the components to fit the requirement of the new use. However, the highest value recovery is with no modification, i.e. using the components as they are. If needed to modify, the components should be modified right after the removal at the deconstruction site. In practice, the contractors do not modify the components themselves, the user has to repair it himself.

Salvage components can be stored at either the deconstruction site, the new construction site or at a designated storage yard. When stored at the deconstruction site, they can be stored virtually without getting deconstructed until a buyer is found. It saves extra transportation and damage to the elements, however, one needs to pay operational costs. Stockpiling has no real cost per se but demands enough storage space on-site and efficient labelling of components. The least preferred is to rent out a yard and store the components there. It leads to extra costs. Transportation is another process involved in the reuse, the component is transported from the deconstruction site to either the end-user, the storage yard or the construction site. From a conceptual point of view, the deconstructed components should be repaired and certified before reuse. However, they are not repaired in practice nor is there any protocol or guideline to certify these components. In the last stage, the components are sold generating revenue. The secondary products after deconstruction are owned by the contractor, the value of which is subtracted from the contract price. The components are sold at 20-50% of the price of new components.

Q4. What are the costs involved in the reuse of structural floor elements?
The active costs incurred throughout the process include the deconstruction, modification, transportation and storage costs while other costs such as the environmental cost, the repair and certification costs are found to be passive as these costs are not paid in practice. The deconstruction process constitutes the highest cost in the reuse process followed by modification, storage and transportation. Therefore, it is better to find a buyer with no modification requirements even when it requires the components to be stored and transported than to sell to a nearby buyer with high modification requirements.

Q5. What is the feasibility condition? What are the tipping points for an economically feasible reuse case?
For an economically feasible reuse case, the net cost of reuse is to be less than or equal to the cost EOL treatment in a traditional demolition. The feasibility condition states that reuse of components is viable only when the total cost of reuse (R_C) is lesser than or at max equal to the cost it incurs to demolish the building i,e, C_{EOL}. For cases when R_C is greater than C_{EOL}, demolition is preferred over deconstruction as extra costs are incurred in deconstruction.
Tipping points are defined as the highest values of variable cost components beyond which reuse of the given component turns uneconomical. It represents the maximum budget that can be spent on a variable cost while keeping the total reuse cost lesser than EOL cost.

Q6. What are the reuse scenarios?
Three different reuse scenarios are developed to analyze the variable costs components of the reuse cost and their interaction with the fixed components. There are three reuse scenarios: Direct On-site reuse (RS1), Direct Off-site reuse (RS2) and Indirect reuse (RS3). The first scenario is RS1 where the recovered products are reused on the same site, i.e, no storage and no transportation cost. The highest cost savings are observed in this case (Glias, 2013). The second scenario is RS2, where the components are deconstructed from one site and taken to another site for reuse. It the second most efficient scenario after RS1 as there is already a demand for the deconstructed components at another site. In the last scenario (RS3), the products are recovered from the building, stored at a facility until a buyer is found and then delivered to the end-user. This is the least desirable scenario but it is most commonly seen in practice.

The results of FCT show that it is most feasible and economic to reuse components directly on the same site (RS1) then to transport them to another site for reuse (RS2). The least feasible option is to store the components and find a buyer for it (RS3) as the process costs of transportation and storage are higher whereas no storage is needed in other scenarios and the transportation is lesser as well. However, for the existing building stock, it is more probable to reuse under RS3 than RS2 and RS1. This is because the existing stock is not designed to be reused and therefore requires greater effort into recovering components for reuse. Instead, a buyer should be found who has no or minimum modification requirements i,e, RS3 case. In a hypothetical condition, if there is a buyer available to consume the secondary components when modified to his requirements, the owners should consider storing the elements for the feasible duration calculated by FCT to find a buyer who wants no modification to the components.

Hence, the criteria for deconstruction should not be the availability of a buyer in advance, it should rather be to find a buyer with no modification requirements even when elements are to be stored or transported. Hence, for RS2 and RS3, the focus should be to find the right buyer with no modification requirements and store the elements or leverage the transportation budget to deliver them to far off the buyer.

Q7. Which factors influence the reuse cost and how?

Various factors are found to affect reuse cost. The results of AHP suggests that "Time Constraint" influences the reuse choices the most. Often the owner wants to get rid of the old building at the earliest to start the new project. However, these strict deadlines set by clients hinder effective deconstruction. The most desirable option is to involve the demolition contractor in the early stages of permit and planning and allow the contractor the time he needs to find a buyer. When there are no time constraints, it gives the contractor bigger opportunities to find buyers for reuse. One can sell the element directly on-site if the time is there, it saves extra transportation and storage cost.

Another factor influencing the reuse cost is the type of connection. The most desirable connections are "dry+ demountable" connections which are developed with the aid of external fixing devices and can be easily taken apart. The dry connections are less-desirable than the former as they are often fixed in place by grouting or with finishing layer. Lastly, the wet connections are undesirable as the component gets damaged once these connections are broken and they need to be redeveloped for reusing the element. Method of construction also affects the reuse cost. It is most desirable when "prefabrication + Design for disassembly (DFD)" i.e. when the prefabricated components are designed to be disassembled at EOL, followed by prefabrication and then cast-in-situ. Having the documents in place reduces the time and effort that goes into the investigation, the risk of accidents and unplanned collapse. Knowing what's inside the building can reduce the modification costs by increasing design considerations well during initial phases.

Other factors such as site accessibility, quantity and age have relatively lower influence over the reuse cost. A site with clear access to all sides of the building is most desirable for as it allows adequate space for material flow, stocking and processing. Site accessibility also determines the method of deconstruction and the level of on-site waste separation. The effect of quantity depends on the value and demand of the product. For a product with high value and demand, the deconstruction in smaller quantities is still profitable whereas, for a product with no buyer, even higher quantities of products find no users. Deconstruction of low- value products in high quantities is economic only when there is already a buyer for it. It is not a good idea to store and look for a buyer for such a product. Lastly, the contractors prefer to deconstruct buildings built before the 1960s which are built of homogenous materials. They are often over-dimensioned and have an aesthetic value which helps to find buyers for reuse.

Q8. How to make reuse profitable?

There are two ways to optimize the reuse costs such that it becomes economically feasible. One way is to increase the budget allocated for reuse by extending the system boundary and the other way is to optimize the process itself by controlling the factors affecting reuse.

The factors affecting reuse costs can be optimized for the worst-case scenario when all the factors are undesirable. The only way to have an economically feasible case in this situation is to allow for sufficient time to balance the costs. The worse case turns economic if the buildings are from post-1980. It implies that it is mandatory to allow for time to deconstruct for prefabricated buildings when other factors are at undesirable stage. In case it is not possible to have the most desirable time constraints, then desirable time which is enough to deconstruct and find the buyer is allocated. In this condition, it is possible only when the buildings are from before 1960 and have at least medium accessibility to the site. When least desirable time constraints are posed, i.e. no extra time is allocated for deconstruction, the break-even point is attained for most desirable age, high accessibility and quantity of recoverable and at least desired level of “the presence of documents”. In other words, if no extra time is given, then the building should at least contain homogenous materials, have easy access to components to reduce execution time and have a good quantity of recoverable product to earn enough revenue such that it gets economically feasible. The reuse budget can also be increased by extending the reuse system boundary and taking into account the environmental impact cost. The economic feasibility of reusing components will increase if the owner/polluter is made to pay for the environmental damage.

Q9. What is feasibility calculation tool? How does it quantify reuse feasibility?
FCT can be successfully used to determine the economic costs and feasibility conditions quantitatively allowing for a circular EOL treatment. The reuse scenario and the tipping points for the structural floor elements can be evaluated well in advance of demolition guidance the decision of the owners to demolish or deconstruct for reuse. A well-planned deconstruction can further help find buyers in time and deconstruct with higher precision as per the requirements of the buyers increasing the salvage cost and the need to modify components after deconstruction.

FCT has been developed in Microsoft Excel. Since the deconstruction cost is a fixed cost whereas the modification, transportation and storage are variable in nature, to achieve a feasible reuse case, different combinations of variable costs are generated using the concept of random sampling. The tool calculates the feasible reuse cases and for these cases, it generates quantitative tipping points for the variable costs. Tipping points are the highest feasible values that can be made for variable costs for a feasible case.

Q10. Does the tool give realistic results?
The tool has been tested on a case study and is found to have no conceptual or technical errors. The validation results for the tool are also positive. It can correctly generate the effect of environmental impact cost and varying salvage on the resultant resue cost and tipping points. Furthermore, the results generated by the tool have been verified with the known facts. For instance, taking the environmental impact of reusing secondary components into account improves the reuse feasibility and the tipping points for reuse case. The reuse cases which are otherwise not economically feasible turn feasible once the environmental impact costs are considered, in other words, once the polluter is made to pay the price. The results obtained from FCT also show the effect the salvage value has on the reuse cost. Higher the salvage, lower is the reuse cost. If components are deconstructed with high quality and sold for higher salvage, the tipping points for transportation, modification and storage get improved i.e. they can be transported for higher distances, stored for a longer time and modified to the requirements of end-user. The sensitivity analysis shows that FCT is sensitive to the changing inputs such as factors affecting the reuse cost.

9.2. Recommendations

This section presents recommendations based on the findings of the research. First, the recommendations for the actors involved in the reuse process are presented followed by the recommendations for future research.

9.2.1. Recommendations for actors

Throughout the research, various challenges were identified associated with the reuse of structural components. This section presents the recommendations for the actors which can help overcome these challenges and realize structural component reuse.

- **Building Owner**: Currently, demolition is a forgotten activity in the planning process. The owner should plan well in advance for the EOL treatment and involve the contractors in earlier stages. The owner should be motivated for deconstructing circularly, allow sufficient time and if he fails to reuse materials himself, he should allow for collection and sale of secondary products by the demolition companies to a third party. The owner should tender to deconstruct as it allows for sufficient planning time and resource arrangement to the demolition contractor with clear guidelines of the outcomes. The tender once out can also attract the nearest buyer.

- **Demolition Contractor:** To battle the demand inconsistency, demolition contractors should try to develop and broaden their network of business. They must collaborate and allow for free sharing of information and residual products. Another approach is to tag along to the existing online platforms and advertise for structural components as well. The contractors should also develop a knowledge base of the project deconstructed in the past to learn the possible challenges and opportunity that can occur in a similar project in the future.

- **Architects and Designers:** Architects and designers should know the materials available for reuse and procure these materials by accommodating them in their design. The practice of pre-purchase of component condemned to be demolished and then developing design around available secondary components can help boost component reuse. They should also use similar structural grids to minimize the modification needed on the components and reuse them at highest value recovery.

- **Government:** Reuse is unlikely to grow if left purely to the market forces, it requires active government legislation support. On the policy fronts, building codes must adapt and provide for alternative solution paths for secondary components. A system of certifications and warranties needs to be formulated by the government to reduce the risks involved. The government should further extend its support in terms of local economic development policies which enable secondary market establishment, creation of employment and training labour.

9.2.2. Recommendations for future research

This section highlights the potential direction for future research

- **Economic feasibility for the whole building:** currently, the FTC can give the economic costs, feasibility and tipping points of reusing only structural floor elements. However, in a real situation, the owner would also want to know the reuse feasibility of other components or the building as a whole. Doing so will allow the building owners to better evaluate their decision and chose the correct components to be deconstructed for reuse.

- **Case Base Reasoning Environment:** In this research, the feasibility is calculated for one office building. The details of the floor elements were available along with their environmental profiles. However, for older buildings, it is unlikely to have this data in place. There, the data of as many existing buildings should be fed to the FCT as possible and the results should be recorded. One can then estimate the feasibility of buildings whose information is not complete by matching it to the projects similar to it. This approach is called case-based reasoning (Tatiya et al., 2018).

- **Futuristic Harvest Map:** This research can be extended to develop futuristic harvest maps on the regional and the national level. Having generated the tipping point for different buildings, they can be added to the digital database creating a portfolio of the secondary component supply. The information on the tipping points of existing buildings can be very useful to match the supply with future building demands. A visual harvest map can be plotted with the reuse boundaries and tipping points of individual buildings. The overlapping boundaries of the buildings on the map with the future building plans can serve as a demand-supplier match. To achieve this, one needs to integrate the FCT with GIS to plot the coordinates and tipping points of existing stock in a region. On a national level, this can be a great tool to help meet the circle economy goals of the Dutch government.

- **Multiple reuse cycles:** This research has worked out the economic feasibility for only a single reuse cycle. Multiple reuse cycle costs aren't considered. Furthermore, the effect of renovation is not taken into account as it often includes changes into the stuff, skin and interior layers of the building and not the structure. However, renovation affects the overall functional age of the building which then determines when a building is to be demolished and deconstructed. It would be interesting to explore the effect of multiple reuse cycles and renovation on the net reuse costs and the tipping points.

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