A BIM-BASED BUILDING CIRCULARITY FRAMEWORK: ASSESSMENT AND VISUALIZATION THROUGH 5R STRATEGIES

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ABSTRACT

A BIM-BASED BUILDING CIRCULARITY FRAMEWORK: ASSESSMENT AND VISUALIZATION THROUGH 5R STRATEGIES

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Principles of the circular economy are applied to improve resource efficiency and reduce environmental impact. The purpose of this thesis is to create a BIM-based framework for building circularity assessment (BCA) that enables an analysis of R strategies such as Reusing, Recycling and Rethinking with graphically aided data representation and supports decision-making starting from the early stages to end of life. To learn more about building circularity indicators and assessment approaches, a literature review was conducted. Then, design alternatives of 5R strategies were developed and modeled into Revit. To analyze the building circularity of these alternatives, Environmental Product Declarations (EPD) were compiled into BIM enviroment with unit values. Before transferring EPD informations into BIM, these datasets are gathered into an Excel file with respect to parameters from BAMB templates such as Global Warming Potential, Deconstructability and Reusability to calculate building circularity. To integrate building circularity assessment to BIM, BCA framework was developed in Dynamo. The framework enables calculating building circularity and generating graphical results in Revit with respect to environmental effect, recoverability, and deconstructability. A case study and its 5R design alternatives are used to test the framework. The outcomes show that solutions that involve Rethinking has the best environmental impact and deconstructability performances, when Reducing owns the best recovery performance. As a result, Rethinking is the best alternative to provide most circular design, since many circular design principles, including sustainability technologies, design for deconstruction and adaptable design, are combined there. The methodology presented in this study makes the process of generating circularity indicators more comprehensible and gives guidance for making decisions regarding the application of R strategies.

Keywords: Circular Economy, Building Circularity Assessment, Building Information Modelling, Sustainability, Multicriteria Approach

ÖZ

BIM TABANLI BİNA DÖNGÜSELLİK ÇERÇEVESİ: 5R STRATEJİLERİ İLE DEĞERLENDİRME VE GÖRSELLEŞTİRME

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Döngüsel ekonominin ilkeleri, kaynak verimliliğini artırmak ve çevresel etkiyi azaltmak için uygulanır. Bu tezin amacı, yeniden kullanma, geri dönüştürme ve yeniden düşünme gibi R stratejilerinin grafik destekli veri gösterimi ile analiz edilmesini sağlayan ve erken aşamalardan başlayarak karar vermeyi destekleyen döngüsellik değerlendirmesi (BCA) oluşturmak için BIM tabanlı bir çerçeve oluşturmaktır. hayatın sonu. Döngüsellik göstergeleri oluşturma ve değerlendirme yaklaşımları hakkında daha fazla bilgi edinmek için bir literatür taraması yapılmıştır. Daha sonra 5R stratejilerinin tasarım alternatifleri geliştirilmiş ve Revit'te modellenmiştir. Bu alternatiflerin bina döngüselliğini analiz etmek için Çevresel Ürün Beyanları (EPD) birim değerlerle BIM ortamında derlenmiştir. EPD bilgilerini BIM'e aktarmadan önce, bu veri kümeleri, bina döngüselliğini hesaplamak için Küresel Isınma Potansiyeli, Yapısızlaştırılabilirlik ve Yeniden Kullanılabilirlik gibi BAMB şablonlarından alınan parametrelere göre bir Excel dosyasında toplanmıştır. Bina döngüsellik değerlendirmesini BIM'e entegre etmek için Dynamo'da BCA çerçevesi geliştirilmiştir. Çerçeve, bina döngüselliğinin hesaplanmasına ve Revit'te çevresel etki, geri kazanılabilirlik ve yapısızlaştırılabilirlik açısından grafiksel sonuçlar üretilmesine olanak tanır. Çerçeveyi test etmek için bir vaka çalışması ve

5R tasarım alternatifleri kullanmıştır. Sonuçlar, Yeniden Düşünmeyi içeren çözümlerin en iyi çevresel etki ve yapısöküm performanslarına sahip olduğunu, Azaltma stratejisinin ise en iyi kurtarma performansına sahip olduğunu gösteriyor. Sonuç olarak, sürdürülebilirlik teknolojileri, yapısöküm için tasarım ve uyarlanabilir tasarım da dahil olmak üzere birçok döngüsel tasarım ilkesi burada birleştirildiğinden, Yeniden Düşünme en dairesel tasarımı sağlamak için en iyi alternatiftir. Bu çalışmada sunulan metodoloji, döngüsellik göstergelerinin oluşturulması sürecini daha anlaşılır kılmakta ve R stratejilerinin uygulanmasına ilişkin kararların alınmasına rehberlik etmektedir.

Anahtar Kelimeler: Döngüsel Ekonomi, Bina Döngüselliği Değerlendirmesi, Bina Bilgi Modellemesi, Sürdürülebilirlik, Çok Kriterli Yaklaşım

Dedication

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ABBREVIATIONS

AEC: Architecture, Engineering & Construction

AP: Acidification Potential

BAMB: Buildings As Material Banks

BCI: Building Circularity Indicator

BEM: Building Energy Model

BIM: Building Informtion Modelling

BWPE: BIM-based Whole-life Performance Estimator

CE: Circular Economy

CI: Circularity Indicator

COBie: Construction Operations Building Information Exchange

EOL: End of Life

EPD: Environmental Product Declarations

GWP: Global Warming Potential

IFC: Industry Foundation Classes

IoT: Internet of Things

LCA: Life Cycle Assessment

LFI: Linear Flow Index

ODP: Ozone Depletion Potential

PEI: Primary Energy Intensity

CHAPTER 1

INTRODUCTION

The exploitation of resources and carbon footprint are both strongly impacted by the building sector. The consequent fast growth in raw material demand is one of the main worries in the twenty-first century (Government of Netherlands, 2016). Construction uses 32% of all material resources in the EU and generates 38% of trash (European Commission, 2018). The aforementioned statistics highlight the critical need for updating the regulations and procedures in the building industry. International organizations work very hard to solve this problem. For instance, Agenda 21 was created by the United Nations to enhance resource sustainability, environmental protection, and public health (UNCSD, 2012). Additionally, the Ellen MacArthur Foundation created a concept and principles for the circular economy between 2013 and 2015 in order to integrate sustainability into building methods (Heisel & Rau-Oberhuber, 2020).

The circular economy is a strategy to decrease the effect of construction materials (CE). CE techniques are suggested as a strategy to increase resource efficiency in order to reduce environmental effects and resource depletion (Eberhardt et al., 2019a). However, the building sector does not frequently use the ideas of the circular economy and resource efficiency (Heisel & Rau-Oberhuber, 2020). The structural stability, durability, ease of disassembly, adaptability, and other issues face the architectural, engineering, and construction (AEC) industry (Al-Obaidy et al., 2022). In contrast to the “take-make-trash” ideas of the linear economy, materials and components integrated into buildings serve as material banks (secondary raw materials) for future construction by staying in the loop and without producing waste (Cossu & Williams, 2015; Hopkinson et al., 2019). The linear economy, which the industrial revolution gave rise to, caused long-term destruction due to resource exploitation and disregard for the limits of the environment (Prieto-Sandoval et al., 2018).

The construction industry employs a variety of tools and techniques to promote the circular economy, including Life Cycle Assessment (LCA), Material Passports (MP), and Environmental Product Declarations (EPD) (Alwan et al., 2017).

LCA has a wide range of applications since it evaluates the environmental effects of buildings and the built environment throughout the course of their entire life cycles (Hossain & Ng, 2018). Material Passports (MP) are being thoroughly investigated as instruments to improve resource and material efficiency in terms of reuse and recycling. Examples include Buildings as Material Banks (BAMB), a Horizon 2020 project financed by the EU called Madaster, and other web-based material passports. BAMB is an electronic collection of material passport data that outlines the qualities of goods' materials that make them valuable for recycling or recovery (BAMB, 2019). Madaster is a platform with an online library of construction-related materials with the goal of decreasing waste by giving items a name (Heisel & Rau-Oberhuber, 2020).

The construction industry's rising trend toward sustainability led to the emergence of several tools in addition to R methods (such as Reduce, Reuse, and Recycle). In order to introduce the circular economy to the construction sector, R strategies are a form of design idea that ranks waste management methods according to their sustainablility level. There are just a few structures that have adopted these methods, despite the fact that they have been the subject of countless studies examining their advantages in terms of the economy and the environment (Atta et al., 2021). This deficiency is attributed to the stakeholders in construction projects' ignorance of the best ways to use building materials at different phases of their lifecycles in a number of studies, including this thesis.

Energy usage and environmental effects are prioritized in the great majority of approaches and procedures for evaluating the sustainability of buildings. Studies on material passports have been carried out (e.g., Honic et al., 2021; Atta et al., 2021), and they demonstrate tremendous potential for integrating CE methods into the AEC sector. Nevertheless, previous studies did not take into account its integration strategy with various retention alternatives to decision making for the end of life scenarios of a construction.

For instance, BWPE, a BIM-based Whole-life Performance Estimator, was developed by Akanbi et al. (2018) to estimate the overall salvage performance at the building level. A prototype BIM software add-in was also created by Di Biccari et al. (2019) to directly show the circularity indications for layered objects like walls in 3D. The circularity evaluation of multiple circularity scenarios for the makeup of a building's end-of-life phase is not taken into consideration by any of the aforementioned methodologies, though. Different R methods are used as alternative scenarios to compare and score them in terms of circularity assessment in a relatively small number of investigations. Tools that can assess a building's circularity while taking into consideration different waste management and circular resource utilization are needed in order to examine the viability of incorporating R methods into the design.

This thesis aims to create a BIM-based knowledge for visually assisted assessment to make it easier to analyze a building's circularity in relation to different R strategies. Finding out how this framework, which has been in place, aids decision-making at all stages, including design and end-of-life, is the goal. The comprehension of the issue and the objectives determines the primary research question:

How can the building circularity assessment be connected with BIM to provide automatically computed analysis of R strategies with graphically supported data representation for non-specialists and give decision-making guidance on the design of the circular building from its early phase to its end-of-life phase?

CHAPTER 2

LITERATURE REVIEW

Chapter 2 provides a full overview of the present research setting on the circular economy, material passports, and their integration into the BIM environment through a survey of the literature. Two steps of the literature review were completed. First, research articles were found and gathered using "Scopus" database searches. The terms "material passport," "sustainability," "end of life," "circular economy," "LCA," and "BIM" were used in the search searches to locate related research resources. Additional criteria were used in the search query to limit the kind of papers returned (articles in English, from civil engineering and architecture fields, and matching of extracted keywords). The chosen articles were then divided into groups using assessment models and circularity indices.

This chapter explains the idea of CE and explains how it is now being used in the building industry. Following that, the CE notion is examined using a number of definitions from different articles. The building circularity assessment's technical components are then looked at in the context of the specified circular building design concepts. This chapter discusses the building circularity indicators and associated evaluation frameworks. The next section outlines the existing methods for this integration of BIM with building circularity assessment.

2.1 The Concept of Circular Economy

It is difficult to trace the precise roots of the CE notion since several prominent schools of thought, including as Regenerative Design, Performance Economy, Cradle to Cradle (C2C), Industrial Ecology, and Biomimicry, have influenced and refined the broad principles (EMF, 2013). Although each of these five schools of thought focuses on a different issue, they all concur that the existing industrial economic system has to be revised. Additionally, they all seek to create healthy interactions between people and nature and lessen the negative consequences of human activities on the environment (Zhai, 2020).

Three guiding concepts make up the circular economy: (1) reduce waste generation, (2) circulate goods and resources (while they are still useful), and (3) restore the environment (EMF, 2015a).

A move toward renewable resources and energy underpins it. A circular economy separates economic activity from the use of finite resources. It is a strong structure that is advantageous to the environment, the economy, and society. The resource flow in a circular economy is depicted in Figure 2.1.

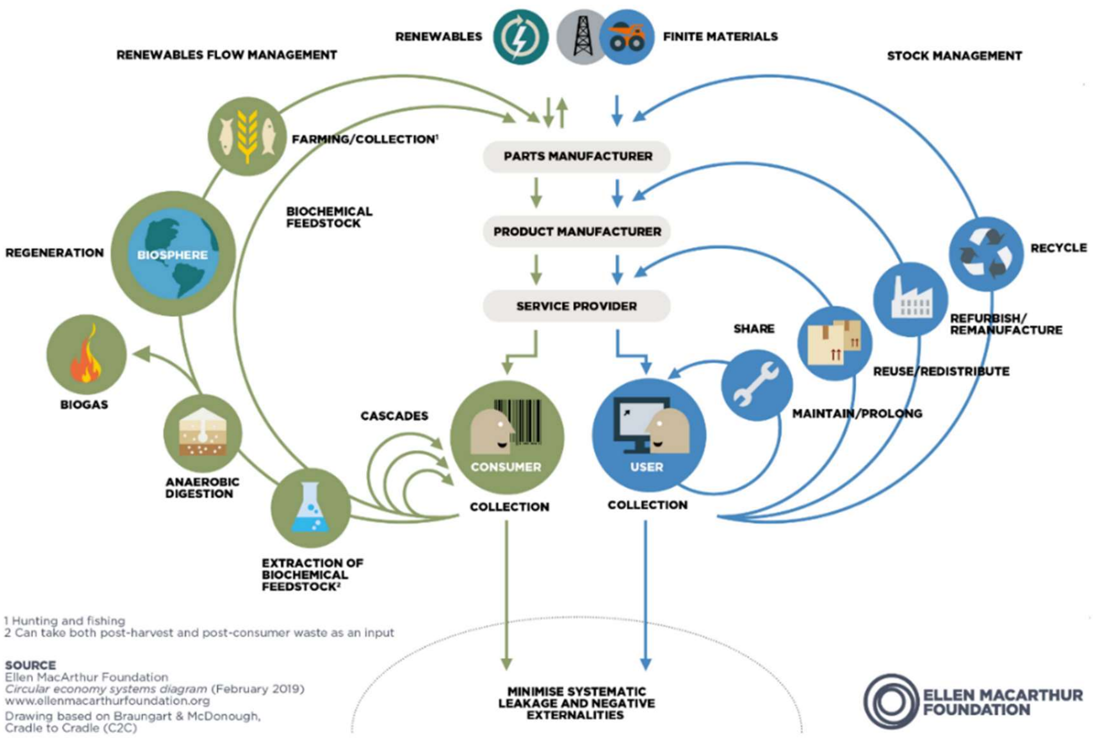

Figure 2.1. The butterfly diagram to visualize CE (EMF, 2015a)

2.2 Circular Economy in Building Construction

Policymakers, academics, and business leaders are becoming more and more familiar with the circular economy (CE), and efforts have been made to conceptually integrate CE with sustainability (Akanbi et al., 2018; Rashid et al., 2013). According to the Ellen McArthur Foundation's definitions (2013, 2015a), CE is a tactic for achieving sustainable development. For enhanced economic and environmental performance of nations, Rashid et al. (2013) underlined the adoption of the circular economy concept in business models and supply chains as a requirement for sustainable manufacturing. While "reduce, reuse, and recycle" is widely used to describe CE, Kirchherr et al. (2017) noted that it is generally disregarded to perform CE from such a systemic approach. Then, they recommended concurrently considering the macro-level (city, region, nation, and beyond), the meso-level (ecoindustrial parks), and the micro-level of the CE system (products, companies, and customers). They also pointed out that the definitions obtained mostly emphasize economic expansion and have shaky links to sustainable development (Kirchherr et al., 2017).

2.3 Building Circularity Principles and R Strategies

Three fundamental ideas were supplied by the Ellen MacArthur Foundation (EMF) to assist individuals understand the CE model (2015a). The first concept is centered on managing limiting resources and coordinating renewable flows to dematerialize the design. The second principle is that in order to optimize resource yields, products, components, and resources should always be circulated at their greatest usefulness. The last tenet focuses on reducing the emission of harmful compounds and other types of pollution.

The butterfly diagram (see Figure 2.2) was divided into two portions by the Ellen MacArthur Foundation (EMF), which included the technological and biological cycles. The illustration shows how the larger outer loops include the smaller inner loops. These inner loops preserve more of the inherent value since they keep a product whole, which is where the greatest value may be recovered. Inner loops that include sharing, maintaining, and reuse should thus take precedence over outer loops that involve disassembling and reconfiguring the product. By using products and resources that are already on the market rather of investing in their manufacture, these loops also save customers and businesses money. Because recycling entails removing a product's intrinsic value and disassembling it into its component parts, it is ultimately the last step in a circular economy (2015a).

A few studies were conducted on R strategies in the AEC sector. By taking into account the manufacturer, designer, and user sides of the product life cycle, Vermeulen et al. (2018) outlined the 10 R strategies—Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle Materials, Recover, and Re-mine. They offer a concluding 10R's hierarchy in the article by definitions and a thorough comparison of the 10R's to clarify the conceptual uncertainty. By utilizing several examples, the Ellen MacArthur Foundation (2015a) described the Sharing, Maintaining/Repairing, Reusing, Redistributing, Refurbishing, and Recycling techniques to establish a circular economy. Tserng et al. (2021) used a case study from Taiwan to illustrate their 5R approach of CE in a construction project. Rethink, Reduce, Reuse, Repair, and Recycle are the tactics. Although the research is not focused on these concepts, Zhai (2020) outlined circular building design principles within three phases of a building life cycle to comprehend the material movement. The manufacturing of materials and components, design, and end-of-life have been utilized as the three key phases of the building lifecycle to arrange particular concepts for circular material utilization and circular design. Of grouping the circular building design ideas by Zhai (2020) into several life cycle stages, Figure 2.2 explains them.

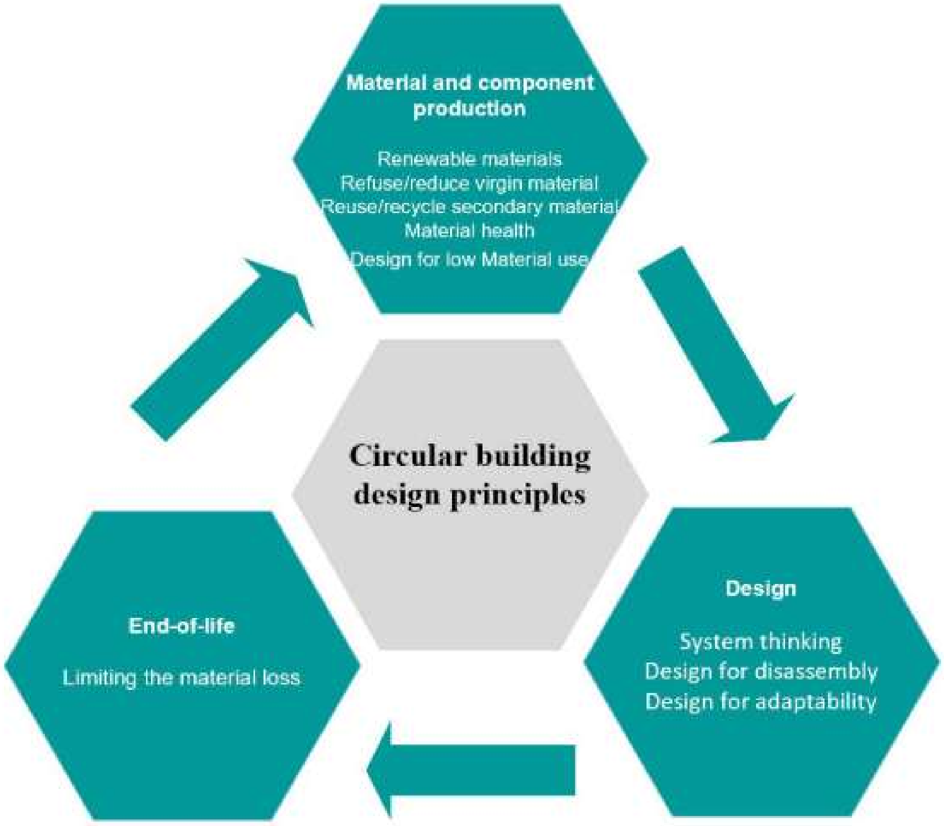

Figure 2.2. Crucial circular building design principles throughout a building life cycle (Zhai, 2020)

Reike et al. (2018) proposed an integrated version of the value retention options mapping that aims to highlight the contribution of new economic actors in product maintenance and repair, refurbishment, and remarketing as well as to remind consumers of overlooked loops in the life cycle stages during product retention, as shown in Figure 2.3. Long before a product is initially mass-produced, its retention option actions are taken into account to map CE choices on the life cycle phases (Reike et al., 2018).

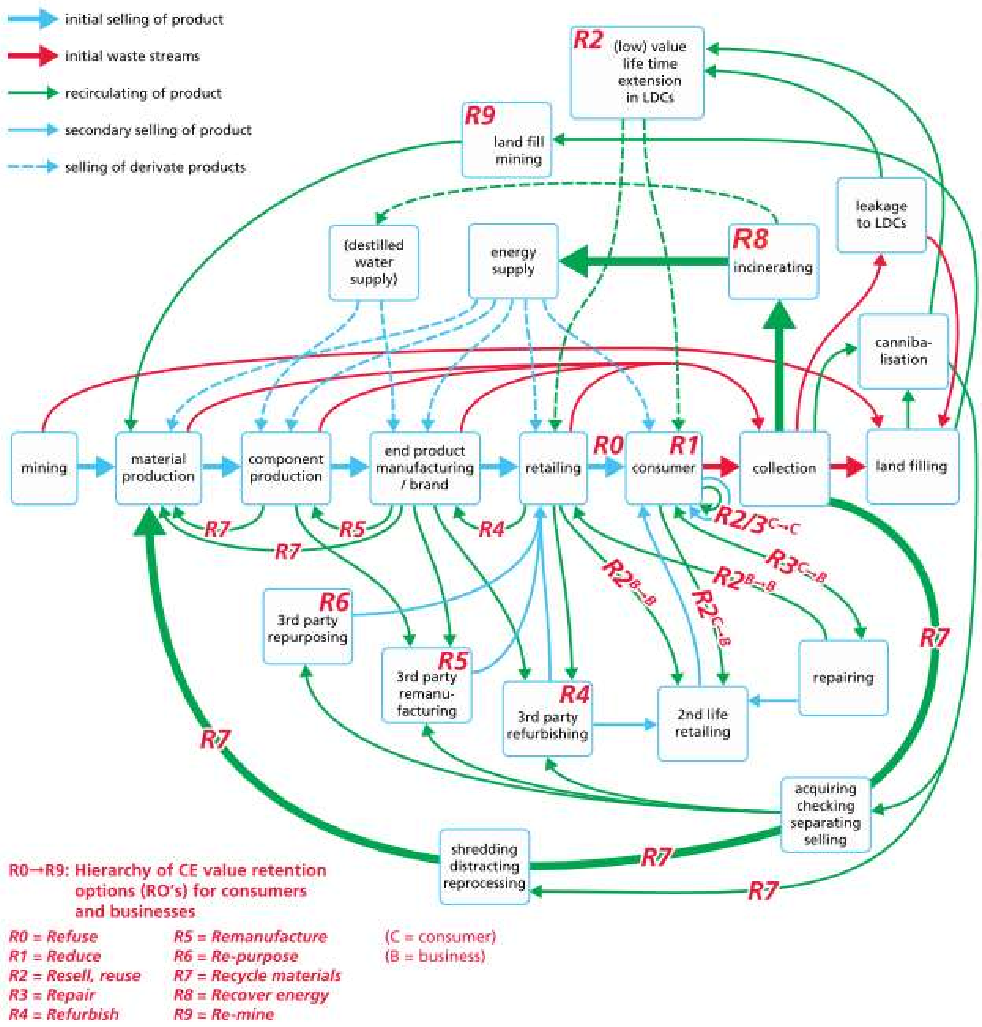

Figure 2.3. Mapping circular economy retention options on product life cycle (Reike et al., 2018)

2.3.1 Sharing

Sharing is the first stage in the Ellen MacArthur Foundation's technological cycle (2015a), and while it is not appropriate for all economic products, it has the potential to dramatically increase the usage of many commodities. With many different sorts of items, sharing is possible. For instance, an increasing number of platforms let users wear clothes from shared closets.

2.3.2 Maintaining

Keeping things in top condition and guarding against deterioration or failure is essential. It is strongly tied to the R-strategies idea of “Repair.” Increasing a product’s value through prolonging its usable life is the aim of the strategy (EMF, 2015a).

2.3.3 Reusing

This phase, like sharing and preserving, makes sure that items are utilized appropriately and in their original form (EMF, 2015a). Secondary materials, as opposed to primary materials, which are entirely fresh, are recycled or repurposed from primary materials that have been left unused. However, it should be noted that recycling may need more energy than extracting a natural resource from the earth. In order to promote the use of secondary resources rather than virgin ones, this concept (Zhai, 2020).

2.3.4 Redistributing

Redistribution is another method for keeping products in use and reduce waste. When goods are transferred from their intended market to another customer, they are effectively utilised (EMF, 2015a).

2.3.5 Refurbishing

Restoring items to good working condition is one way to raise their worth. This could comprise making repairs or replacements of parts, improving the specs, and improving the appearance.

Refurbishing may be done by either individuals or experts on their own items. The Right to Repair movement aims to change regulations to enable for the easy performing of simple repairs on products (EMF, 2015a).

According to Vermeulen (2018), refurbishment requires keeping a big, multi-component product's overall structure while replacing or repairing a significant portion of its components to generate an overall "upgrade" in product quality.

2.3.6 Remanufacturing

A multi-component product's whole structure is dismantled in an industrial process, scrutinized, cleaned, and, if required, replaced or repaired; recycled parts may be utilized (Vermeulen et al., 2018).

Remanufacturing is done when things can't be retained in circulation in their current form and need extra effort to be utilized again. Remanufacturing is the process of re-engineering products and parts such that they look and function at least as well as newly created products. Remanufactured items or parts are frequently sold with a warranty that is equal to or higher than that of the newly manufactured product (EMF, 2015a).

2.3.7 Recycling

The Ellen MacArthur Foundation's technological cycle is finished with recycling (2015a). Products that have passed the point of no return and cannot be fixed, upgraded, or remanufactured fall under this category. It's the only way left to keep the product's basic materials from going to waste.

When a product is recycled, the time and labor that went into making it are wasted, but the value of the raw materials is maintained. Recycling is the process of disassembling a product or component into its component materials or component parts, then reprocessing those components to produce new materials.

2.3.8 Reducing

Dematerialization, another name for reducing, was included in the EMF's circular economy tenets. Less material is required for the creation of each unit using this technique. In other words, the plan stops disposing, which eliminates waste (Vermeulen et al., 2018). Utilizing lightweight design, prefabricated modules, energy- and water-saving technology, the method may be applied to the building industry (Tserng et al., 2021).

2.3.9 Rethinking

Examples of the principle known as "rethinking" include making a product more user-intensive, substituting services for parts, and reinventing ideas, processes, and product dynamics. It aims to enhance resource efficiency through innovative concepts and applications including material passports, sharing ownership, and pay per lux (Tserng et al., 2021).

2.3.10 Recovering

By definition, recovery refers to the process of extracting energy from waste and transferring it to the production of energy, distilled water, or biomass through combustion (Vermeulen et al., 2018). Two types of recovery were explained by Shooshtarian et al. (2019). Utilizing a waste product, such as recycling it or recovering energy or other resources from it, is known as waste recovery. When other methods of material recovery are not economically or technically feasible, when there is community acceptance of the processes involved in energy waste, when there is a steady supply of feedstock, and when the intended materials have a high calorific value, energy recovery is a viable option for residual waste.

2.3.11 Re-mining

After the period of landfilling, materials are recovered by re-mining. It closely resembles the idea of "cannibalization." It's called cannibalization when repairable components are taken from one piece of equipment and put on another. Urban mining or high-tech landfill mining are used to extract useful resources from an element (Vermeulen et al., 2018).

R techniques have been connected in the literature to certain life cycle periods where they lessen the influence on the environment. Re-mining, recycling, and recovering are more closely related to the material's end of life and recovery phase. These can be used throughout the manufacturing stage as well. A producer can process mixed streams of post-consumer product or post-producer waste to acquire nearly qualified materials, capture energy contained in waste and link it to incineration in accordance with producing energy, and extract components after the landfilling in order to implement these strategies into the life cycle. Sharing, reducing, reusing, rethinking, and mending are more directly tied to the design and operational stages. Utilizing recycled materials, acquiring stuff that was not or scarcely being used, repurposing abandoned things modified for another use, and allowing simple repair are a few methods to put these concepts into practice while creating or running. Remanufacturing, refurbishment, and redistribution are more closely related to a material's manufacturing stage. While many of a big, multi-component product's components are changed or repaired, the main structure of the product can be left intact, leading to an overall "improvement" in product quality. Another approach is to take a multi-component product apart from top to bottom and replace or fix a part as necessary. These procedures are the means through which these strategies are to be applied to the product life cycle.

Sharing, reducing, reusing, and mending are consumer-focused practices that may be used by for-profit or nonprofit organizations to lengthen the useful life of products. The main driving force behind refurbishment, remanufacturing, and rethinking is usually commercial activity, and those involved are normally highly knowledgeable, specialized third parties. According to Vermeulen, “traditional waste management strategies” include mining, recovering, and recycling (2018). They are, however, also the possibilities for retention on which government circular economy 1.0 and 2.0 plans have been centered. They are essential to the effort to use recovered materials to more valuable applications. Because more quantitative data is available, multiple R methods from various scales are used in this work, particularly from consumer and business sizes.

2.4 Building Circularity Assessment

In order to identify, promote, and develop key performance indicators for circularity throughout the built environment, several initiatives and projects have been carried out in Europe since the 2000s (Al-Obaidy et al., 2022). In recent years, a variety of ideas have been created and applied in sustainability research, including material passports, Environmental Product Declarations (EPD), life cycle assessment (LCA) methodologies, and digital twins.

A Material Passport is a qualitative and quantitative record of the building materials that were employed. It displays the materials used, their effects on the environment, their capacity for recycling, and how they are incorporated into the building (Honic et al., 2019a). As part of the Buildings As Material Banks (BAMB) initiative, 15 partners from seven different European countries have developed a material passport for buildings since September 2015. (BAMB, 2019). To achieve high recycling rates, in-depth knowledge of the current stock and embedded materials is necessary. However, our lack of knowledge regarding the actual material composition of the existing building stocks is the main obstacle to obtaining high recycling rates (Honic et al., 2019a). The range of BAMB material passports includes materials, goods, and systems. It can establish the worth of a substance for recovery. It can list the general characteristics of goods and systems that make them attractive for recovery, such their design for disassembly, but it can also go extremely detailed about a particular good or system in its usage. The link between a product and a structure, for instance, is vital to understanding a product's worth for recovery (BAMB, 2019). How to use quantitative KPIs to support design decision-making is another issue (Nuñez-Cacho et al., 2018). In 2018, the need for EPDs across the entirety of Europe made it feasible to conduct a uniform, unbiased LCA-based assessment of the impact of building materials (Al-Obaidy et al., 2022). Manufacturers can offer comparable, unbiased, and independently verified information about how well their products and services perform in terms of the environment, including the good, the bad, and the ugly (EPD International, 2022). Eberhardt et al. proposed a method for circular building design assessment, for instance, in 2019. The method is used to a construction that follows the DfD (Design for Disassembly) guidelines. Where data were lacking, estimating methods and assumptions based on technical datasheets were used, along with EPDs for various components and materials (Eberhardt et al., 2019a). Many LCA programs also include EPD material for these assessments, which is useful for creating EPDs. For instance, EPDs that have been added to the One Click LCA database include thorough technical descriptions of building components and are in compliance with EN15804 and/or ISO 14025 standards. A typical EPD has a five-year validity term and is generated in compliance with the relevant standards. Construction EPDs are built upon the ISO 14040/14044, ISO 14025, EN 15804, or ISO 21930 standards (OneClick LCA, 2022).

By expanding upon and personalizing the Material Circularity Indicators for the needs of the construction sector, the Madaster Foundation developed the Circularity Indicator (CI). The Circularity Indicators score each building's circularity between 0% and 100% based on the information users have supplied to the site. When a building is being landfilled after a usage time that is shorter than average and has a Madaster Circularity Indicators of 0%, it is considered to be completely "linear" (Heisel and Rau-Oberhuber, 2020). The Madaster platform also makes it feasible to document, discuss, and assess these design decisions by using a similar set of values and indices (Heisel et al., 2019).

The SPHERE BIM Digital Twin Platform was developed by the European Commission and provides a synchronized, unique building-centered digital twin environment (PaaS). This makes it possible for the operations involved in its design, manufacture, construction, and operation to be vertically integrated. Various stakeholders can interact with this Digital Twin model at any time during the building's lifecycle using data about the structure and a scalable collection of different software tools like energy demand/performance simulation tools, Decision Support and Coaching Systems, BEMs, or IoT enabled Predictive Maintenance Algorithms (BIM4EEB, n.d.). The methodology used in SPHERE for the environmental evaluation is the standardized approach to LCA as outlined by many standards and guidelines. Figure 2.4 outlines how the SPHERE environmental assessment framework's life cycle stages are defined by the EN 14643-2:2011 standard (SPHERE, 2020).

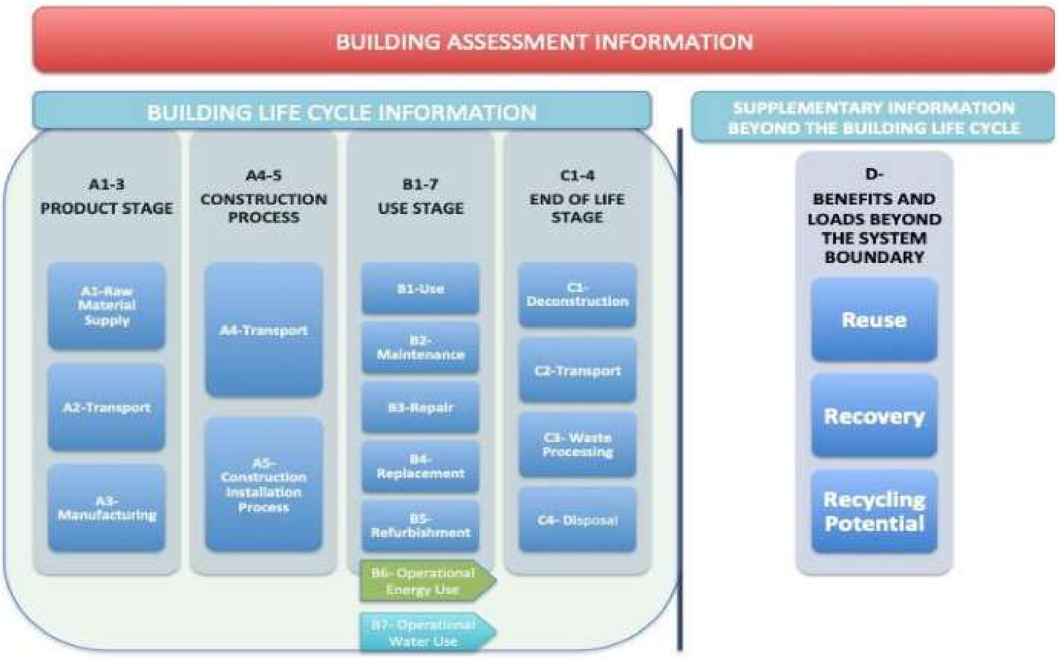

Figure 2.4. Life Cycle Information as defined in standard EN 14643-2:2011 (SPHERE, 2020)

2.4.1 Building Circularity Indicators

Construction circularity indicators and the technical properties of building materials and components are connected (Zhai, 2020). Three kinds of circularity indicators were presented by Mesa et al. in 2018. The first set of sustainability performance indicators consists of the Linear Flow Index for Product Families, the Potential Reuse Index, and the Potential Recycle Index. These metrics keep track of the product's potential flow of recyclable and reusable materials. According to Eq. 1, the linear flow index for product families calculates the proportion of material flow from raw materials to trash that cannot be used. The indicator is calculated as the ratio of the total quantities of material from the product family flowing linearly and restoratively to the quantity of material from the product family flowing linearly.

$$Linear\ Flow\ Index = \sum_{j=1}^{n} \frac{V_j + W_j}{2M_t + \frac{W_{fj} + W_{cj}}{2}} \qquad \text{Eq. 1}$$

where, *Linear Flow Index: sum of Linear Flow indexes for all product variants*
V_j: *mass of virgin feedstock used to manufacture j product variant*
W_j: *mass of unrecoverable waste associated with j product variant manufacturing*
M_t: *total mass of the product variant*
W_{fj}: *mass of unrecoverable waste generated when producing recycled feedstock for the j product variant*
W_{cj}: *mass of unrecoverable waste generated in the process of recycling parts for the j product variant*

A statistic to determine the likelihood of component reuse across several product versions within a family of goods is the Potential Reuse Index. The need for improved capabilities or modifications to the operating level of a particular parameter, such as volume, height, or mass, is connected to the implementation of a reuse strategy (Mesa et al., 2018):

$$Potential\ Reuse\ Index = \frac{\sum_{i=1}^{n} M_{ri} * k_i}{M_t} \qquad \text{Eq. 2}$$

where, *M_{ri}: mass of reusable component i*
k_i: number of times the component is reused in the product family from product variant 1 to product variant n
M_t: total mass of the product family

The Potential Recycle Index is defined as an assessment of the potential for some degree of product family component recycling. The lifespan of a new product is circular because component recycling lessens the need for primary raw material extraction (Mesa et al., 2018):

$$\text{Potential Recycle Index} = \sum_{i=1}^{n} \frac{M_i F_i E_i}{M_T} \qquad \text{Eq. 3}$$

where, *M_i: mass of the i component*
F_i: fraction of recyclable mass of the i component
E_i: efficiency of the recycling process for the same component
M_t: total mass of the product family
n: number of modules or components involved in the product family

Reconfiguration Index, Functional Range Index, and Functional Variety Index make up the second set of metrics, known as functionality performance indicators. The Reconfiguration Index describes the relationship between the complexity of a product family and the quantity of possible reconfigurations. A component can be used in several alternate configurations in various product variations. As a result, the statistic evaluates the trade-off between the product's complexity and the range of reconfigurations it offers.

The Functional Range Index illustrates the relationship between the product family's operational capability or size and complexity. According to the formula created by Mesa et al., a higher Functional Range Index is highly desirable when a modularization technique is adopted into a product family (2018).

The functional Variety Index measures the relationship between the quantity of functions and the complexity of the product family. It is desirable to boost this signal if the targeted product family can offer more features for a given complexity and the complexity of the product family has lowered (Mesa et al., 2018). Due to the variety of users, frequency of use, and emphasis on ultimate disposal, data collecting is difficult during the use and EOL (end of life) stages. These markers provide a potential method for quantifying trash. The recommended collection of measurements, however, is unrelated to typical environmental metrics like emissions, resource consumption, or energy use. Integrating these CE signals with conventional indicators is crucial to guarantee sustainability throughout the product lifecycle (Mesa et al., 2018).

Environmental impact indicators including Global Warming Potential (GWP), Acidification Potential (AP), and Ozone Depletion Potential have been used in several research papers utilizing the Life Cycle Assessment technique of circularity assessment models (ODP). The ecological consequences are considered, for example, in the study by Honic et al. (2019b), as sustainable buildings and materials must be avoided if they have a major negative influence on the environment. IBO (Austrian Institute for Building and Ecology) has acknowledged the crucial elements from the traditional LCA methodology that are necessary for the measurement and optimization of ecological footprints after performing comprehensive literature studies and foundational research. The IBO is an independent, non-profit scientific institution that conducts research on the interactions between people, buildings, and the environment (IBO - sterreichisches Institut für Bauen und kologie, n.d.). IBO considers the three indicators of buildings' GWP (Global Warming Potential), AP (Acidification Potential), and PEI (Primary Energy Intensity) when evaluating the environmental effect utilizing the LCA methodology and repository (Honic et al.,2019b). The 2020 research by Zimmermann et al. is another illustration of how the Life Cycle Evaluation technique has been modified to compute circularity assessment. In order to account for existing buildings on the construction site when assessing structures and to portray the framework on a building case, they developed a framework based on the current criteria of LCA for buildings. This framework is exhibited on an existing educational structure. These scenarios involve new building, rehabilitation, and preservation. LCAbyg software is used to effectively manage existing buildings in the Danish construction context by taking into account a building's GWP. With the use of the current framework, the LCA may be improved so that existing structures, even those slated for removal on construction sites, are taken into account (Zimmermann et al., 2020).

Deconstructability and recoverability (reusability/recyclability) were two important circularity evaluation indicators in addition to the LCA methodology. Atta et al. (2021) developed a framework to include Material Passports (MP) into BIM. It is essential to include the MP in sustainability assessment techniques. Because these technologies are available, stakeholders may evaluate various building options and compare them before construction begins. Three indicators—the deconstructability score, recovery score, and environmental score—were used by Atta et al. in 2021. The deconstructability score indicates how quickly its constituent parts can be disassembled. Demountable connections promote circular building that may be taken apart and reused, giving building materials a sustainable end-of-life scenario (Atta et al., 2021). The purpose of this indicator is to assess how effectively the design guideline "Design for disassembly" is implemented. The recovery score describes how much of the building's materials and components can be salvaged. The score is based on how many components are recyclable and reused. Uncoated construction materials and non-toxic materials are viewed as crucial elements that facilitate material recovery (Atta et al., 2021). The LCA values for comparable construction materials are calibrated in a way that affects the environmental score. It also takes into account the expanded lifespans of construction materials (Atta et al., 2021). The provided indicators combine environmental performance indicators with practicability indicators, but the environmental score may be challenging to calculate because it depends on a lifecycle inventory database that is not always available. Other scores, however, are straightforward to calculate because they depend on statistical data from the sound model (Atta et al., 2021).

$$\mathrm{Dc} = \frac{\sum Demountable\ Connections}{\sum All\ Connections}$$

$$Rp = \frac{\sum Prefabricated\ Elements}{\sum All\ Elements} \qquad \text{Eq. 4}$$

$$Dscore = \frac{Dc + Rp}{2}$$

Eq 4. Deconstructability score (Atta et al., 2021)

Demountable connections are believed to comprise bolts, interlock, and dowels in the study by Atta et al (2021). In contrast, fixed connections are said to be made through welds, glue, and nails. The proportion of demountable connections (Dc) and the proportion of prefabricated pieces are the factors that influence deconstructability (Rp). In light of these key characteristics, the deconstructability score (D-score), which ranges from 0 to 1, is assessed.

$$\mathrm{Rscore} = \frac{Rc + Ru + Nx + Ns}{4} \qquad \text{Eq. 5}$$

Eq 5. Recovery score (Atta et al., 2021)

where, *R_c: ratio of the building elements that are recyclable*
R_u: ratio of the building elements that are reusable
N_x: ratio of the building elements that are non-toxic
N_s: ratio of the building elements that are uncoated

A higher number indicates better material recovery. The score ranges from 0 to 1. (Atta et al., 2021).

2.4.2 Building Circularity Assessment Models

Building circularity evaluation approaches like Verberne's BCI and the Madaster Foundation's CI have received attention from studies and corporations (Verberne, 2016; Madaster, 2018b). To identify the circularity of the building, Zhai (2020) looked at six suitable evaluation models and contrasted them based on input, output, advantages, drawbacks, and supporting tools. These evaluation frameworks are known as the Material Circularity Indicator (EMF, 2015b), Building Circularity Indicator (Van Vliet, 2018; Verberne, 2016), Building Circularity Index (Alba Concepts, 2018), Circularity Indicators (Madaster, 2018b), and Platform CB'23 (2019).

To measure the extent of circularity at the product level, a for-profit web-based application called Material Circularity Indicator was developed (EMF, 2015b). The approach evaluates the amount of a linear flow and restorative flow for the materials that make up the product and compares the lifetime and intensity of a product with comparable industry-average goods. It is a widely used device that is used in many investigations. However, just the technical cycle is taken into account; no assessment of circularity from different stages of the building is undertaken (Zhai, 2020).

The Material Circularity Indicator for a Particular Product (MCIp), followed by the Product Circularity Indicator (PCI), the System Circularity Indicator (SCI), and lastly the Building Circularity Indicator, is the first stage in the BCI model (Verberne, 2016). (BCI). It investigates the links and physical interfaces at the assembly in a building by taking into consideration the circularity from various levels of the construction. However, Dutch construction has not embraced it as a certification or labeling system (Zhai, 2020).

Van Vliet (2018) updated Verberne's (2016) BCI model after addressing its flaws, notably in calculating the likelihood of disassembly. The PCI, SCI, and BCI computing methods used in Van Vliet's BCI model are distinct while maintaining the same hierarchy. It also considers circularity from different building elevations. It also provides a comprehensive framework to assess the building's deconstruction potential. Sadly, it has not also recognized it as a certification or labeling system (Zhai, 2020).

Alba Concepts (2018) developed the Building Circularity Index (BCIX) methodology, an evaluation approach that identifies a building's level of circularity. The BCIX technique includes three important KPIs: the Product Circularity Index (PCIX), Element Circularity Index (ECI), and BCIX. PCIX is built on the Material Index (MI) and Disassembly Index (DI). The use of the building circularity evaluation model, consideration of circularity from multiple building levels, and calculation of the percentage by mass of each individual indicator for the total structure are only a few advantages. But it hasn't been accepted as a certification or labeling system either (Zhai, 2020).

The Madaster Foundation established Circular Indicators (CI) based on the MCI specifically for the construction sector (EMF, 2015a). Their CI assesses a building's degree of circularity throughout the duration of its whole existence. Similar to MCI, CI gives each building it examines a score between 0 and 100%. A structure is completely "linear" if it is zero percent linear (Heisel & Rau-Oberhuber, 2020). If a structure is composed entirely of reusable, recyclable, or swiftly regenerated materials and can be readily disassembled and re-used after its usage phase, it is said to be totally "circular" and obtains a 100 percent CI score. According to Alba Concepts' The Building Circularity Index (BCIX), it has probably been put into practice (2018). Additionally, it considers the circularity of the structure from the perspective of all its lifecycle stages. However, it does not assess the circularity from different building elevations (Zhai, 2020).

Since Platform CB'23, the construction sector has been attempting to define a core technique to measure circularity (2019). The three primary goals of circular construction—the preservation of current material sources, the protection of the environment, and the preservation of current value—form the foundation of its computation. The platform is still being developed, though, and has not yet been published (Zhai, 2020).

2.5 Integration of Building Circularity Assessment and Building Information Modelling

In order to assess the most current BIM-BCA integration methods, Zhai (2020) assembled and reviewed five articles and tools. According to this study, there are two primary streams of BIM-BCA integration. The first option is to employ a data exchange standard (such Industry Foundation Classes (IFC) or Construction Operations Building Information Exchange (COBie)) to retain the BoM and other aspects of BIM model parts. The shared data are then assessed using outside software, such as an internet platform, that assesses the circularity of structures. The first stream includes both the Madaster (2018b) and the circular building assessment (CBA) prototype (BAMB, 2019). As a substitute, the evaluation might be performed with BIM software by putting up special parameters in a BIM tool like Revit to capture various characteristics of a building's circularity. The BIM-based Whole-life Performance Estimator (BWPE), the Steel Structure Deconstructability Assessment Scoring (SS-DAS) tool, and the BIM-based Deconstructability Assessment Score (BIM-DAS) tool are all included in the second stream (Zhai, 2020). With the help of these evaluation techniques utilizing BIM software, it is possible to develop unique parameters in Revit to transfer different attributes and evaluate the environmental performance in a way that is more usable for those with a low level of expertise. The BWPE tool was created as an Autodesk Revit add-in using the Revit Application Programming Interface (API), Visual Studio, and the C# programming language. BWPE is a difficult tool to install into a project since it requires deep understanding of programming languages and the Revit programming interface. Advanced technical tools are also required to analyze a project's circularity by non-specialist engineers and architects. Additionally, the SS-DAS tool exclusively assesses the deconstructability of steel buildings, making its application in just a small portion of the circular economy particularly specialized.

In order for the mathematical model to evaluate the building's whole-life performance by estimating its recovery performance based on design specifications and decaying, Akanbi et al. (2018) used a BIM-based Whole-life Performance Estimator (BWPE) to characterize structures and their salvage characteristics. A BWPE is created by explaining the issue, creating a mathematical model, solving the model mathematically, running the model, and deciphering the outcomes. BWPE was a component of the BIM environment that was added to Autodesk Revit. With the help of the Revit Application Programming Interface (API), Visual Studio, and the C# programming language, the BWPE capabilities may be integrated with the Revit software (Akanbi et al., 2018).

Jayasinghe and Waldmann (2020) created a Building Information Modeling (BIM)-based system that will allow the circular economy by successfully managing material recycling and component reuse. This program serving as a Material and Component (M&C) bank was developed using PHP and MYSQL by utilizing a web browser that can extract the materials and component information of a building from the BIM model.

2.6 Existing Gap in Literature

The current state of the art and the desired state are investigated to find out the existing gap in the literature. The majority of the established frameworks and tools are restricted to giving quantitative indications, as considered by the research in Table 2.1. When the literature is investigated in a more detailed way, there are several gaps, which are significant to specialize the scope of the study.

Table 2.1. Contributions of existing literature

References	LCA	BIM Based	Material Passport	R Strategies	Visualized Data
Akanbi et al., 2018		●			
Çetin et al., 2021		●	●		
Eberhardt et al., 2019	●	●			
Heisel & Rau-Oberhuber, 2020		●			
Atta et al., 2021		●	●		
Jayasinghe and Waldmann, 2020		●	●		
Al-Obaidy et al., 2022	●	●			
Zimmermann et al., 2020	●				
Tserng et al., 2021				●	
Zhai, 2020		●	●		●
Zhang et al., 2021			●		

Firstly, the selection criteria for indicators are not well defined. The relevance of each indicator is not justified. For those without specialized knowledge, some of the indications are challenging to comprehend, such as Eutrophication. Many earlier tools omit practicability indicators in favor of merely providing environmental performance measures. These studies remain challenging to implement in a building practice due to the indicators' lack of comprehension. This gap is also stated in Atta et al.'s study (2021). However, their suggested indicators can be implemented in the representation of environmental results.

Secondly, visualization of circularity assessment results is not provided in the investigated research in Table 2.1. Only in Zhai et al.'s study, circularity results are represented graphically; however, they only considered circularity results instead of circularity indicators and their total scores. For the purpose of enhancing the comprehension of the necessary information, visual representation is a crucial tool for data display. The results of circularity assessments are difficult for non-specialists to understand. To convert the application of circularity into real practice, it is crucial to visualize the circularity indicators. However, there is insufficient information in the existing literature about how to visualize comprehensive circularity data in relation to the project.

Lastly, there are many studies explaining and considering R-strategies; however, investigated studies do not consider these R-strategies in different design alternatives and compare their effectiveness in reducing environmental effects of the buildings. For instance, one design option favors reusing strategies, whereas another does so for reducing strategy. Undoubtedly, there should be one option that does not use any R-strategies. By implementing different R strategies into design alternatives, the comparison of alternatives aids in decision-making and assists construct a more sustainable project.

In addition, inventory databases of different building materials include a number of useful data for Reusing, Recycling, and Recovering. These tactics are chosen to be used in this research because to the simplicity with which the indicators associated with them may be calculated. To lessen the negative effects of building on the environment and the economy, reducing is also known as dematerialization of construction. One of the intended design possibilities relates to the Rethinking approach by utilizing more environmentally friendly technology, such as green roofs, or by putting the design deconstruction ideas into practice, or by altering the geometry of the structure. It is feasible to compare the circularity of one design option and the others to determine the impact of the Reducing approach by leaving out certain beautiful but unneeded materials or shrinking one. The Rethinking approach is the use of greener materials in various design possibilities. All design possibilities are contrasted in order to comprehend the implications of the various R methods. These 5 R techniques offer more useful data and indications that can be more precisely calculated. As a result, this study adopts the five R’s of recycling, reusing, recovering, reducing, and rethinking.

In order to close these gaps, the research suggests a BIM-based framework tool that takes into account the findings of the circularity evaluation. Making judgments is made easier and more quickly when R-strategies are prioritized, which speeds up circular building design. The BIM-based framework offers guidance on how to apply building materials to various plans and design options. It also provides a graphical presentation of circularity evaluation data to help architects and engineers analyze various options while taking the comprehensiveness of indicators into account. The approach of bridging this gap is discussed in the section that follows, which also recommends a framework program built on BIM and has enhanced visualization of the circularity of construction materials.

CHAPTER 3

METHODOLOGY

A suitable technique is critical to reaching the study objective and responding to the research questions. It makes it easier to carry out a structured and effective research procedure, which increases the possibility of gathering solid information and yielding useful findings. The study approach is thoroughly discussed in Chapter 3.

This study uses a methodological approach that mimics and tailors the Design research methodology (DRM) (Blessing & Chakrabarti, 2009). The four main phases of Design Research Methodology (DRM) are Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II (Zhai, 2020). The three main stages of the design research methodology used in this paper are a literature review to establish the research goal and develop insights (Research Clarification and Descriptive Study I as one stage), software and tool testing to create a prototype and decide the final form of the method (Prescriptive Study), and a case study to confirm the results (Descriptive Study II). Aiming to define and develop the objective in line with the expanded knowledge supplied by the literature study, the first two stages of the Design Research Methodology are essentially condensed into one step.

The first chapter of this thesis, Introduction, is referred to as the Research Clarification step in DRM (Zhai, 2020). The researcher develops a practical and worthwhile research goal—to create a research study—through literature research (Blessing & Chakrabarti, 2009). In contrast to Zhai, as Research Clarification and Descriptive Study I are combined into one stage in this article, the Literature Review section also assisted in establishing the research aim as in the Introduction part. The goal of the Descriptive Study I stage is to comprehend the current situation and its contributing aspects using various methodologies (Blessing & Chakrabarti, 2009). Since the comprehension of the subject may be easily generated through the literature review, this stage mostly pertains to the literature review. The Prescriptive Study corrects and elaborates the original description of the ideal condition from the research clarification stage to make it genuine (Blessing & Chakrabarti, 2009). To implement this solution, this stage also includes prototype development. As a result, this study's Prescriptive Study stage is comparable to the original concept. Since the study starts to provide realistically desirable answers and suggests various means to infer the solution, the methodology chapter mainly refers to that stage. The goal of Descriptive Study II is to investigate the effects of the assistance and its capacity to create the desired environment (Blessing & Chakrabarti, 2009). The stage is connected to a case study to assess the utility of the suggested remedy and the created prototype against the success criteria. The case study might also be designed to evaluate several design options and validate the technique. Figure 3.1 summarizes the stage-by-stage explanations of the study's approach.

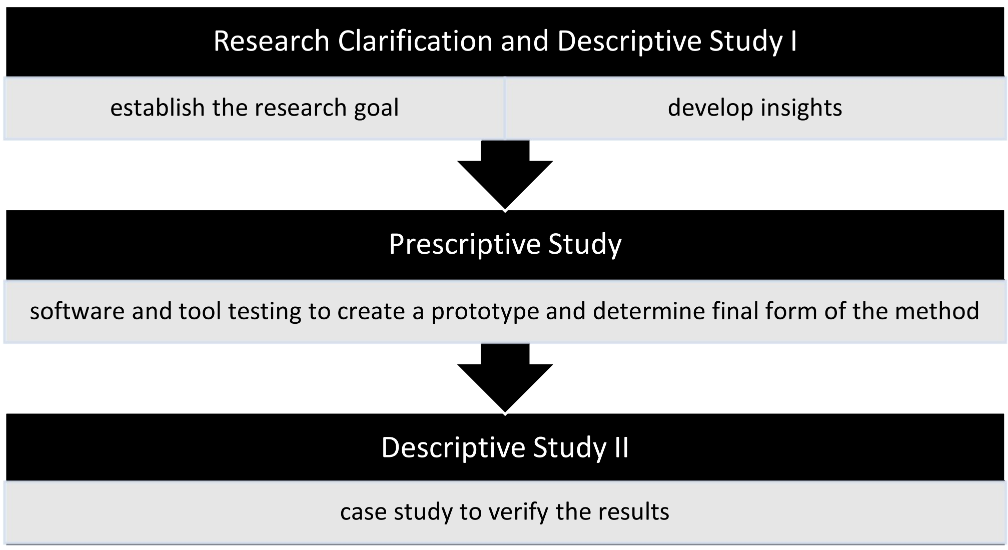

Figure 3.1. Methodology with respect to Design Research Methodology

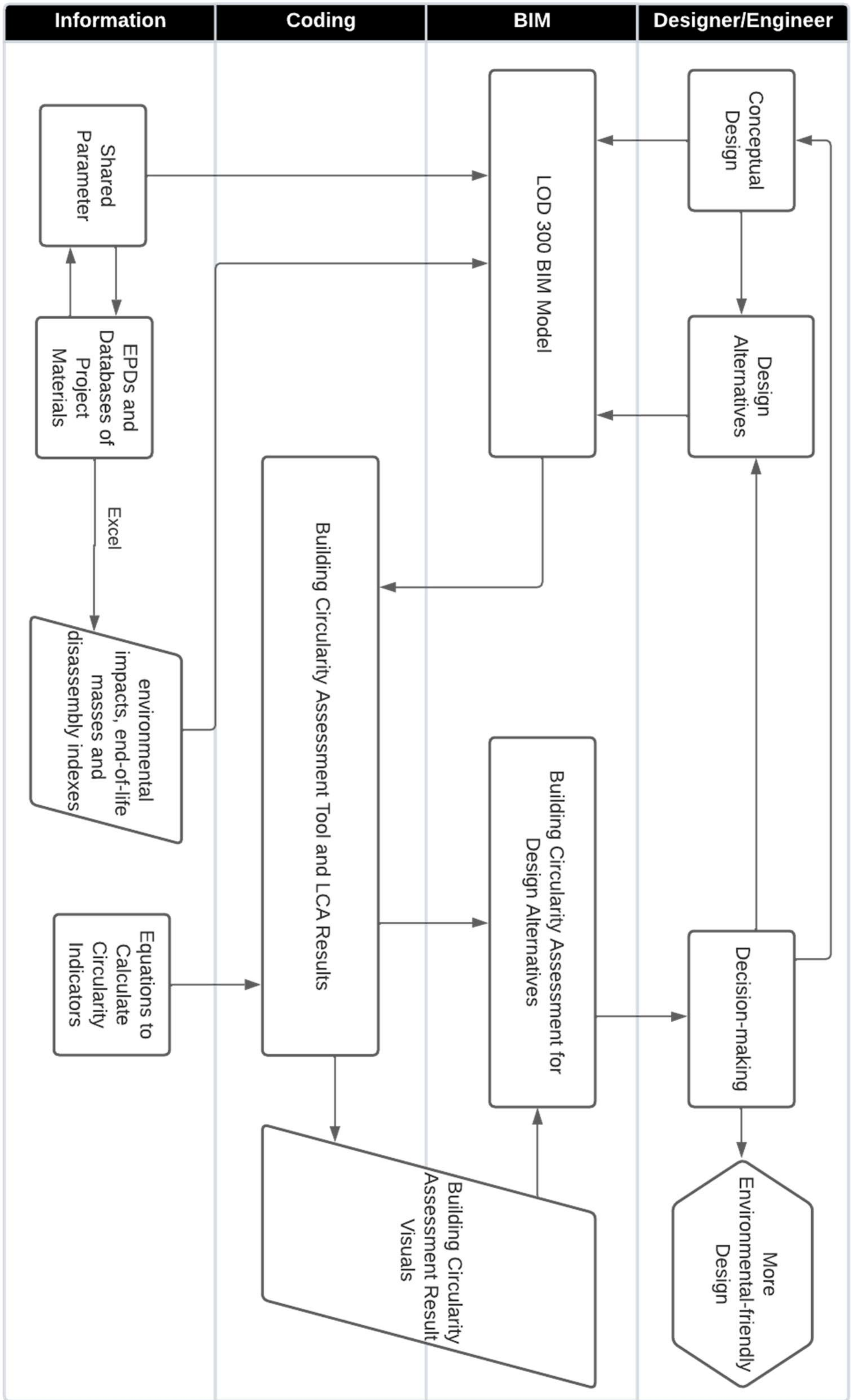

Figure. 3.2. BIM-based Building Circularity Assessment Tool Framework

Figure 3.2. shows the graphically assisted BIM based Building Circularity Assessment framework. To begin with, conceptual design and design alternatives are produced by designer and they are modelled in BIM environment. In this thesis, LOD 300 model was created due to its certain information about quantities, form, orientation and location which are required in building circularity calculations. Required parameters are transferred into shared parameters of BIM environment to make collaborative design possible. The required parameters can be found on different material passport templates such as BAMB. Then, required information about construction materials are extracted from EPDs, databases and material passports. Since they are formatted differently to transfer into BIM, an Excel file is utilized to gather them into a transmitable format. After all of these information about construction materials are imported to BIM, building circularity indicators such as environmental impacts, deconstructability and recovery indices are calculated in Dynamo. In Dynamo, equations to calculate recovery and deconstructability indices such as Potential Reuse Index, Potential Recycle Index and Linear Flow Index are processed. Moreover, Life Cycle Assessment can be calculated in Dynamo by multiplications of required units, services lifes and unit environmental impacts from EPDs and their sum. LCA results, building circularity assessment by indices and deconstructability are depicted by color gradients in BIM models of design alternatives. As a result, these visual results are helpful to decision making process of design alternatives to achieve more environmentally friendly design.

For more precise results from the building circularity assessment framework, there are some tips to take care of. Firstly, information about construction materials from EPDs, material passports or databases should be precise. Especially end-of-life scenarios of the products, product contents and environmental impact results in various phases must be accurate for true visual results. Secondly, BIM models should have enough level of details which determine quantity, size, form, location, and orientation. LOD 200 is a minimum level of detail in preliminary building circularity assessment in early design stages (Zhai, 2020). Higher level of details can be resulted more precisely, since the details of the model is closer to as-built version of it (LOD

400-fabrication, LOD 500-as built). Lastly, information about shared parameters should be transferred into BIM models fully. All parameter values should be entered into all model elements to be calculated in Dynamo, otherwise Dynamo cannot run the script without warnings and the result visuals will be blackout.

3.1 Input Parameters

The Autodesk Revit® 2020 building information modeling (BIM) program was used to construct the 3D model with LOD 300. A symbol or other generic and schematic representation is used to graphically depict the project's LOD 100, which is its core model. The LOD 200 model offers a generic object with still approximate amount, size, shape, placement, and orientation. The LOD 300 is graphically represented in the model as a specific system, in which the object has precise values for its dimensions, shapes, locations, and orientations. LOD 400 is depicted as a specific system, where the object has certain dimensions, a specific shape, a specific position, a specific amount, and an orientation, as well as other information regarding how it was created, put together, or placed. LOD 500 is a verified representation that has been assessed on-site in terms of size, shape, location, quantity, and orientation. To compute building circularity evaluation, information concerning quantity, size, shape, position and orientation are necessary. Therefore, in the basic building circularity evaluation during the early design stages, LOD 200 should represent the minimal level of detail.

Figure. 3.3. Level of Details (AIA, 2013)

Product features such as environmental impacts, input and output flows and deconstructability data from EPDs were integrated into the Revit model by manually entering these parameters. The EPDs are used to incorporate the LCA findings for the materials into the BIM environment. Environmental impact findings are estimated in accordance with the life cycle analysis criteria of ISO 14040, 14044, and CEN 15978 standards for all EPDs used in this study.

Due to Dynamo's wide variety of capabilities for visual programming, it was employed for the outcomes of circularity indicators. It made it possible to analyze environmental outcomes from product EPDs and derive several factors from those outcomes. The way of visualizing the findings and additional specific information about these parameters are given in the sections that follow.

3.2 Data Collection (Inventory Analysis)

Depending on the level of the inquiry, several data collection techniques are employed. During Stage I Descriptive Study, the vast majority of the evidence is acquired from the literature using the appropriate keywords in Scopus. Literature review enabled understanding the existing approaches and shaping the methodology used in the current research.

By entering the keywords into The International EPD System during the Research and Descriptive Study II stage, environmental results, input and output flows to define the reusability or recyclability of products in the design alternatives are retrieved from EPD product files (Figure 3.2). According to ISO/TS 14027, 14025, 14040, 14044, and 14067, the program is carried out. For building materials, the EPD program complies with ISO 21930 and European Standard EN 15804 (A1 and A2). The International EPD System welcomes participation from both public and private entities from the majority of countries and across all product categories (EPD International AB, n.d.).

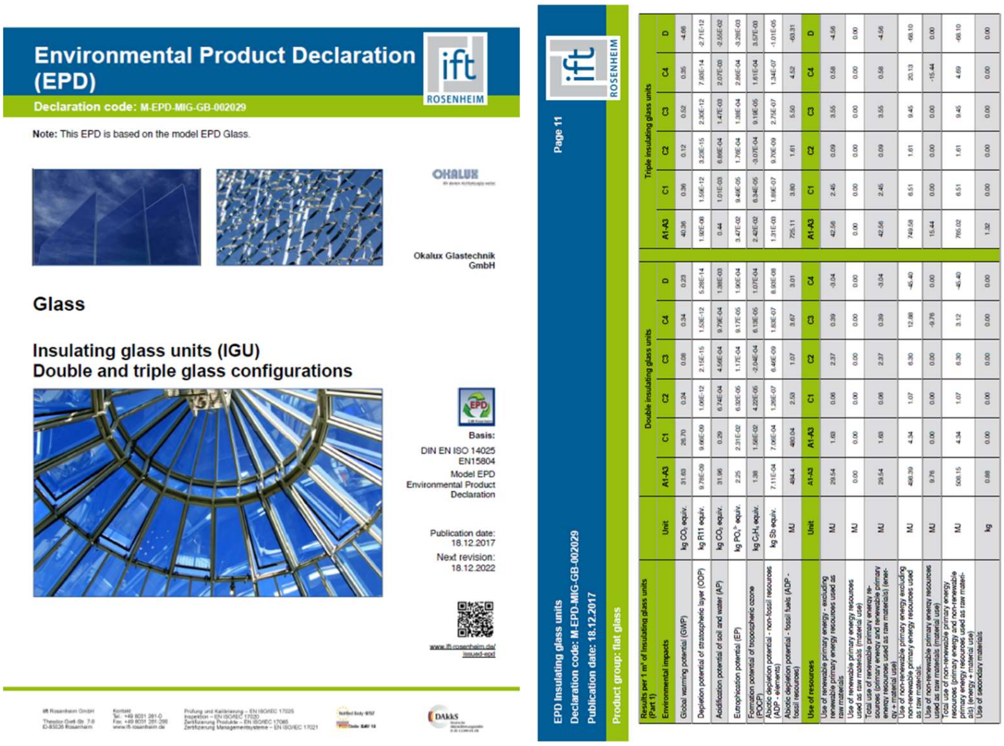

Figure 3.4. An EPD example used in the study

After gathering EPDs to define the material properties in BIM model, firstly these data sets are added into BIM environment as a unit. Then, material takeoffs are taken from Revit and converted to an Excel file to compute the real and total values of product values of parameters from EPDs by applying previously mentioned calculations. Figure 3.3. shows the material takeoff of one of the 5R alternatives. These excel files are only used for converting unit values into normal values.

Material							
Name	**Unit**	**Unit Conversion**	**Useful Life**	**Climate Change (A)**	**Climate Change (B)**	**Climate Change (C)**	**Climate Change (D)**
Adaptable Meeting Rooms Double glazed 3m x 3m	Volume	0.046296296	876000	3913.7	0	401.179	-7.65E+02
Partition Wall-glazed	Area	1	350400	5.65E+01	0	0	0.00E+00
Partition Wall-blind	Area	1	350400	3.10E+01	0	0	0.00E+00
Adaptable Wall (AW)	Area	1	876000	46.239	0	17.4486	-9.48E+00
Adaptable Meeting Rooms Single glazed 3m x 6m	Volume	0.023148148	876000	5756.9	0	360.31	-1.16E+03
Adaptable Walls			**665760**	**1960.8678**	**0**	**155.78752**	**-386.896**
Bituminous Membranes made of Recycled Polyester	Area	1	175200	0.458	0	0	0.00E+00
Non-reinforced EPDM membranes for waterproofing	Area	1	262800	2.414	0	5.33E-01	0.00E+00
multi-layer panel made of a high density bitumen based membrane and a porous textile layer	Area	1	438000	14.925	0	0.0869	0.00E+00
two layer product made of a self-adhesive high density bitumen membrane thermally bonded to a cross-linked polyethylene	Area	1	438000	0.19013	0	0.0029	0.00E+00
Bituminous Membrane			**328500**	**4.4967825**	**0**	**0.1557**	**0**
Curtain walls and punched windows	Area	0.153846154	219000	1.42E+03	0	30	-1.04E+00
Curtain wall systems	Area	1	262800	186.6	5.71E-01	13.992	-2.81E+01
Insulating glass units (IGU)-STRUGAL	Area	1	262800	86.5	0	2.5932	-15.3
Insulating glass units (IGU)	Area	1	262800	31.63	0	27.36	2.30E-01
Low-e double Glazing	Area	1	262800	33.1	9.50E-02	0.337	0.00E+00
M60 Curtain wall aluminium system	Area	1	262800	1.40E+02	0	2.689	-4.16E+01
Curtain Walls			**255500**	**316.305**	**0.111**	**12.82853333**	**-14.30166667**

Environmental Impacts									
Acidification (A)	**Acidification (B)**	**Acidification (C)**	**Acidification (D)**	**Eutrophication (A)**	**Eutrophication (B)**	**Eutrophication (C)**	**Eutrophication (D)**	**Ozone Depletion (A)**	**Ozone Depletion (B)**
18.4336	0	0.48949	-4.36E+00	0.483559	0	0.0101877	-1.28E-01	0.00045047	0
3.40E-01	0.00E+00	0.00E+00	0.00E+00	6.32E-02	0.00E+00	0.00E+00	0.00E+00	7.34E-06	0.00E+00
1.32E-01	0.00E+00	0.00E+00	0.00E+00	4.18E-02	0.00E+00	0.00E+00	0.00E+00	4.69E-06	0.00E+00
0.31441	0	0.005764	-5.04E-02	0.00761186	0	0.0000916	-2.08E-03	6.9795E-06	0
27.6864	0	0.56096	-6.39E+00	0.755158	0	0.0121388	-2.02E-01	0.00063463	0
9.381282	**0**	**0.2112428**	**-2.16008**	**0.270265772**	**0**	**0.00448362**	**-0.066416**	**0.000220822**	**0**
0.00227	0	0	0.00E+00	0.000401	0	0	0.00E+00	4.71E-08	0
0.01056	0	9.30E-04	0.00E+00	0.002275	0	2.74E-03	0.00E+00	0.000000569	0
0.071289	0	0.000551	0.00E+00	0.0074831	0	0.0000717	0.00E+00	2.50745E-05	0
0.00111969	0	0.00001842	0.00E+00	0.00111969	0	0.00001842	0.00E+00	4.02257E-08	0
0.021309673	**0**	**0.000374855**	**0**	**0.002819698**	**0**	**0.00070753**	**0**	**6.43271E-06**	**0**
1.20E+01	0.00E+00	0	-3.79E-03	3.78E-01	0.00E+00	0.001	-8.37E-05	7.80E-05	0.00E+00
1.38671	2.37E-03	0.05705	-2.26E-01	0.067157	6.48E-05	0.0005298	-1.13E-02	0.000021036	2.79E-08
0.744	0	0.009414	-0.203	1.35	0	0.02462	-0.355	5.90E-04	0
31.96	0	0.292109	1.38E-03	2.25	0	0.0233719	1.90E-04	9.78E-09	0
0.16213	4.99E-04	0.002443	0.00E+00	0.00008013	3.23E-05	0.000000687	0.00E+00	2.56E-07	4.39E-09
8.90E-01	0.00E+00	0.0179	-2.97E-01	1.73E-01	0.00E+00	0.0004945	-4.18E-02	1.77E-05	0.00E+00
7.85714	**0.000478167**	**0.063152667**	**-0.121401667**	**0.703039522**	**1.61833E-05**	**0.008336148**	**-0.06799895**	**0.000117834**	**5.38167E-09**

	Input and Output Flows							Deconstructability	
	mass of recyclable component	**mass of reusable component**	**number of times the component is reused**	**total mass**	**The Linear Flow Index**	**Potential Recycle Index**	**Potential Reuse Index**	**Demountable**	**Prefabricated**
0	352.2	851.05	1	1593	0.622332078	0.221092279	0.534243566	TRUE	TRUE
0	22.1635	76.32	1	100	0.436861	0.221635	0.7632	TRUE	TRUE
0	11.571	0.00E+00	1	100	0.322881	0.11571	0	TRUE	TRUE
0	1.4	25.595	1	32.7	0.587232416	0.042813456	0.782721713	TRUE	TRUE
0	352.2	851.05	1	1593	0.622332078	0.221092279	0.534243566	TRUE	FALSE
0	**147.9069**	**360.803**	**1**	**683.74**	**0.518327714**	**0.164468603**	**0.522881769**		
0	0	0	0	100	0.605	0	0	FALSE	FALSE
0	0.00E+00	0.00E+00	0.00E+00	7	1	0	0	FALSE	FALSE
0	0	0	0	100	1	0	0	FALSE	FALSE
0	0	0	0	100	1	0	0	FALSE	FALSE
0	**0**	**0**	**0**	**76.71946766**	**0.90125**	**0**	**0**		
0	41.6958	0.4502	0	268.4	0.921486587	0.155349478	0	FALSE	TRUE
0	125	0.00E+00	0	300	0.633333333	0.416666667	0	TRUE	TRUE
0	125	0.00E+00	0	300	0.633333333	0.416666667	0	TRUE	TRUE
0	7.50E-01	0.00E+00	0.00E+00	2.5	0.85	0.3	0	FALSE	TRUE
0	0	0	0	20	1	0	0	TRUE	TRUE
0	3.00E+01	0.00E+00	0.00E+00	1.00E+02	0.85	0.3	0	TRUE	TRUE
0	53.74096667	0.075033333	0	165.15	0.814692209	0.264780469	0		

Figure 3.5. Excel file example used in the study

The input data from the EPDs were converted into several BAMB templates using BRE's data Templater. By directly conveying the new BAMB characteristics, this template enhances any software that offers "extensions to its parameters". The template helps us to compile parameters and their values that are utilized in BIM environment to describe materials. However, a software issue prevents moving on with copying the parameters from the template. As a result, these characteristics are manually transferred to the BIM environment.

Environmental Indicators, Reversibility and Maintenance, and End of Life Disposal Options are the three sections of the transferred parameters. Different kinds of environmental impact criteria related to Life Cycle Assessment, input and output flows, which are significant in formulations of potentials to recycle or reuse, and deconstructability are included in the parameter groupings. The current characteristics from product EPDs are complied to create several of these indices.

3.3 Building Circularity Calculation Method

Data preparation, analysis, and visualization are the three main facets of the system architecture that enable the visual depiction of circularity outcomes. Revit was used to manually prepare the data based on the EPDs of the construction elements. In addition to the geometric information, such as volume and area, needed to calculate the circularity of the structure, the BIM model also includes category codes to identify building components. The external database houses the circularity data for building components, which is saved in an excel sheet based on EPDs. Data analysis was performed using Excel, constituting the primary input data into the BIM model. It was possible to improve the circularity assessment through the calculation of various indicators using product properties from EPDs stored in Excel files and primary input data from the BIM model, including total environmental impacts and the percentage of waste that was dumped in landfills, recycled, reused, or recovered components (see Eq. 1-5 in Chapter 2). The modified datasets were then converted to Revit models so that Dynamo's visual programming add-in could represent them analytically (Figure 3.4).

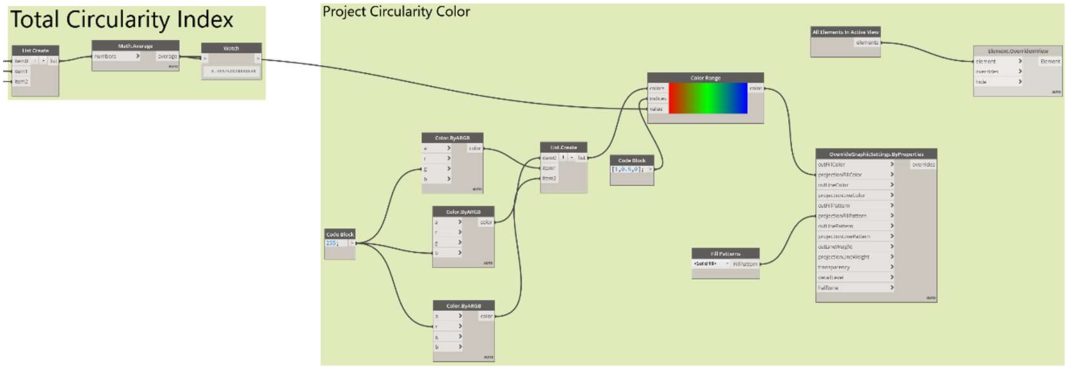

Figure 3.6. Sample Dynamo scripts to calculate Building Circularity (see Appx.A)

The computation of the circularity of the building was done using Dynamo scripts. The recoverability, environmental impact, and deconstructability indices are the three essential components that make up Dynamo scripts, as shown in Figure 3.4. First, based on Equations 1 through 3 and Equation 5, all recoverability scores are created in the command group “Recoverability,” which also includes the computation of the linear flow, reusability, and recycling indexes. The next phase is the creation of a project-related index of environmental effects based on EPDs. The environmental effects of the various items were included as a unit in Excel files before the findings were multiplied by the length, area, volume, or weight of the products. Then, they are exported to Revit from Excel. As in the study by Atta et al., equation (6) is used to normalize the outcomes of single scores within each construction category to determine the adjusted environmental performance (E_i) for each building material (2021).

$$E_i = 1 - \frac{R_i}{R_{max}}$$

Eq. 6

(Atta et al., 2021)

where, environmental performance (E_i)
R_i is the environmental impact of the material i
R_{max} is the maximum environmental impact.

$$Building\ Circularity\ Score = \frac{R_{score} + D_{score} + E_i}{3} \qquad \text{Eq. 7}$$

where, R_{score} is the recovery score,
D_{score} is the deconstructability score, and
E_i is environmental impact index.

Recovery score, deconstructability score and environmental impact scores are averaged to obtain an index for building circularity score for the project. These factors are the most critical assets to make structures more circular.

The last step is to calculate Eq. 4 using the true/false boolean and its sorted lists in the Dynamo scripts for deconstructability. EPDs and BIM models of a couple of the construction parts were used to determine the feasibility of demountability and prefabrication. Lists of demountable and prefabricated items became countable and may be expressed with various color overrides thanks to true/false Boolean operations. Additionally, Atta et al. (2021) quantified the deconstructable elements by calculating the deconstructability score using lists.

3.4 Visualization Method of Circularity Results

Dynamo scripts were coded in three sections: connect component inputs, computation, and display. A group of nodes is present in each part to perform the required function. Every component of the BIM model is connected to the associated circularity indicators thanks to the data connection section. Due to Dynamo's compatibility with Revit's visual programming language, integrating BIM components is made feasible by a variety of selection options. The entire set of model components was chosen all at once for this study. Then, as described in the previous section, indicators for environmental impact, deconstructability, and recoverability were calculated. Based on Equations 1 to 6, Dynamo scripts were developed to compute and modify environmental indicators of the products using Boolean lists, quantify them, place the results of an environmental impact into a range, and generate an index based on the range. Finally, to demonstrate whether pieces can be deconstructed or not, several indicators such as environmental consequences, deconstructability, and recoverability were shown as color gradients (Blue to Red symbolizes Lowest to Highest) and Green/Anthracite for True/False lists.

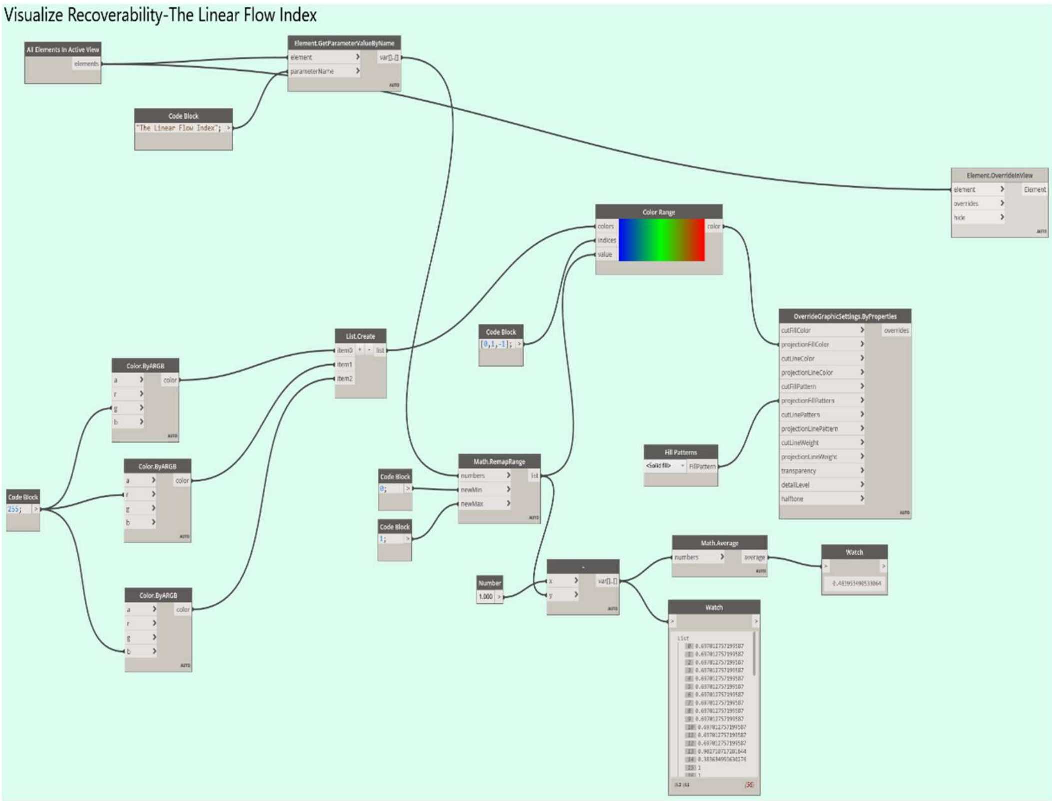

Figure 3.7. Dynamo Scripts for Visualization

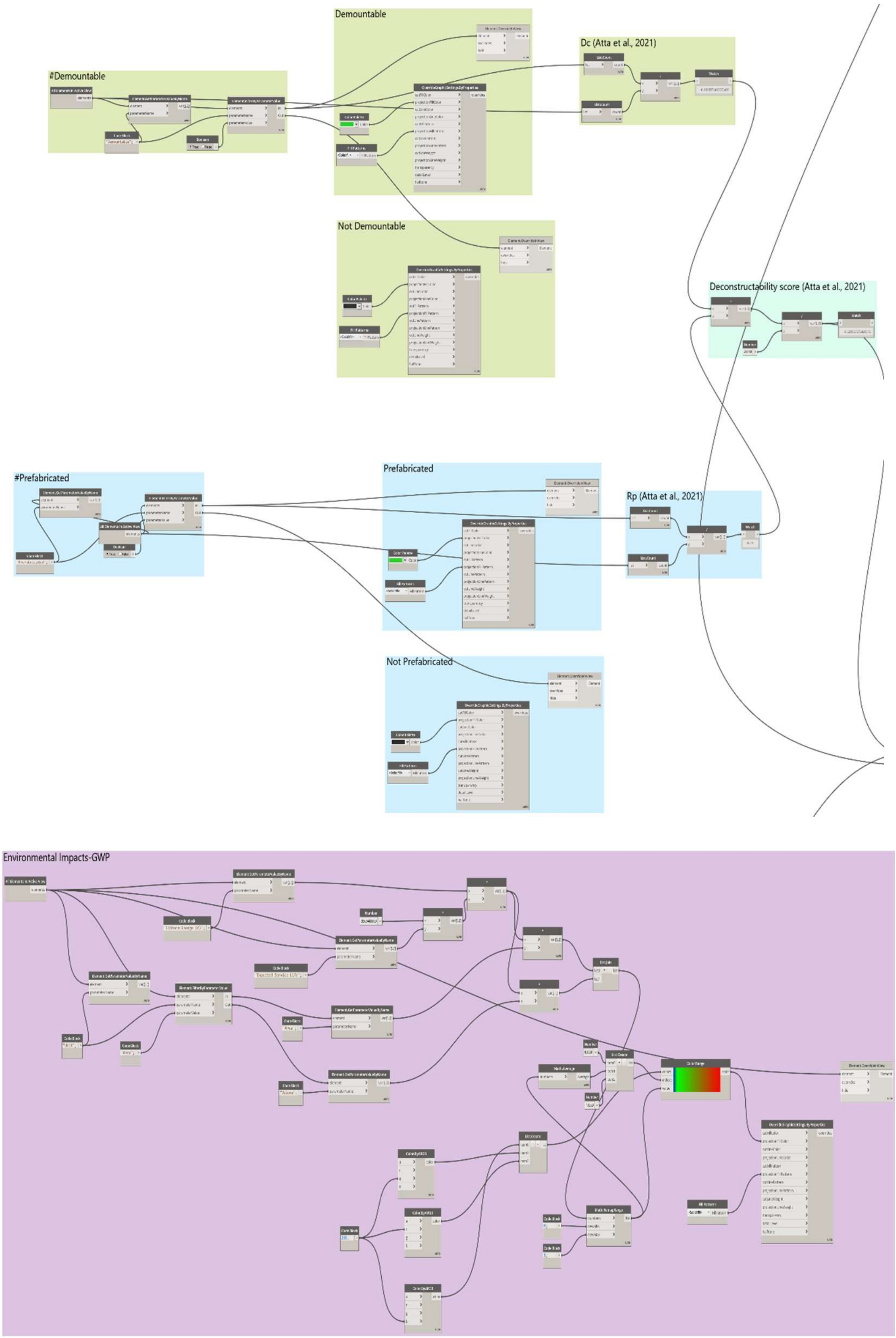

Figure 3.7. Dynamo Scripts for Visualization (cont'd)

3.5 Case Study

Following a thorough analysis of case studies from several sustainable development certifications, such as Passivhouse, LEED, and BREEAM, the design solutions for the case study were determined. By taking into account circular economy theories and the 5R strategies—recycling, reusing, recovering, reducing, and rethinking—the best environmentally friendly design options are presented. These tactics were selected since the necessary measurements for the building materials were readily available, as were workable mathematical techniques. Additionally, compared to the other methodologies, their integration into the BIM model is more useful in modeling.

Table 3.1. Design alternatives

Design Alternatives	
R Strategies	**Design Changes**
Original	-
Recycling	-More recycled materials, such as steel structure
Reusing	-Reusing components -More service duration due to reuses -Design for Deconstruction
Recovering	-Design for Deconstruction -Using materials for energy production
Reducing	-Using more lightweight materials to make structure lighter -Adaptable structure
Rethinking	-Change in orientation, window/wall ratio -Adaptable structure -Using more environmental friendly products

The case study structure is a steel structure for a retail in Stuttgart, Germany that was planned to built in 2022 but is cancelled after. The design was once created as a conceptual design. Then, architectural details were added but mechanical and electrical installations of the detailed design were not completed before the cancel of the project. Therefore, an imaginary version of the retail building was utilized in this thesis to testify the framework. In this thesis, any electrical or mechanical design was not considered into BIM model, but they can be taken care in more detailed designs such as an exemplary real case in discussions section. The case study makes use of R methods to analyze various designs' circularity scores in order to identify the elements that might improve the building's sustainable growth (see Table 3.1).

In the end-of-life stage, steel has the highest rate of recycling, according to a Kreier (2022) article. Additionally, a variety of building supplies, including bonding and connecting bolts, may be created from recycled steel. Steel serves as the primary structural component in the "Recycling" design choice.

After 60 years of usage, the structure is presumptively dismantled in the reusing option. Because they are simple to dismantle (designed for deconstruction), the EPDs used in that design option are chosen based on their capacity to be reused and the proportion of recycled materials they include.

The design alternative of recovering also uses the design for deconstruction technique. Ease of deconstruction is crucial in making the building component available for energy generation at the end of its useful life. Additionally, wood is used as a structural component in the alternative design since it can be burned to provide heat.

Construction using fewer materials that results in trash has a better chance of being recovered. Many lightweight materials, therefore, emit less hazardous residues into the atmosphere. This reasoning establishes the rationale for the decreasing design option.

Rethinking is an approach that modifies a building's characteristics to make it more sustainable, such as orientation, window-wall ratio, construction technology, or construction materials. The plan seeks to incorporate passive design concepts into the undertaking and explore the possibilities of locally available building materials to minimize resource consumption and waste. Moreover, adaptability of design is also important in reducing carbon footprint. In Rethinking alternative, rooms are designed as an adaptable open plan, which walls can be added to adjust the room for any function or needs. As a result, changes were made to the building's orientation, materials, window glazing style, and roof structure. The building materials used in the various design options are shown in Table 3.2.

Table 3.2. Construction materials in the design alternatives

Construction Materials in the Design Alternatives						
Design Alternatives	Floor	Exterior Wall	Glazing	Columns	Beams	Roof
Original	Wood Flooring Concrete Lightweight Metal Deck Steel Bar Joist	Insulated Precast Concrete Wall-20 cm	Curtain walls and punched windows	Steel Column	Steel Beam	EPDM Membrane Rigid Insulation Metal Deck Steel Bar Joist
Recycling	Recycled Raised Floor Panels Concrete Lightweight Metal Deck Steel Bar Joist	Recycleable Precast solid concrete walls ECO 30	Curtain walls and punched windows	Steel Column	Steel Beam	Bituminous Membranes made of Recycled Polyester Earthwool Insulation Metal Deck Steel Bar Joist
Reusing	Recycled Raised Floor Panels Concrete Lightweight Metal Deck Reusable Steel Bar Joist	Prefabricated Timber Frame Wall System 20 cm	Insulating glass units (IGU)	Reusable Steel Column	Reusable Steel Beam	EPDM Membrane Reusable Roof Insulation Boards Metal Deck Reusable Steel Bar Joist
Recovering	Oak Flooring Plywood, Sheathing Wood Joist/Rafter	Prefabricated Timber Frame Wall System 20 cm	Insulating glass units (IGU)	Glue Laminated Timber	Glue Laminated Timber	EPDM Membrane Rigid Insulation Metal Deck Roofing Battens
Reducing	Wood Flooring Concrete Lightweight Metal Deck Steel Bar Joist	Adaptable Room Walls	Adaptable Room Windows	Steel Column	Steel Beam	EPDM Membrane Rigid Insulation Metal Deck Steel Bar Joist
Rethinking	Oak Flooring Plywood, Sheathing Wood Joist/Rafter	Adaptable Room Walls	Adaptable Room Windows	Glue Laminated Timber	Glue Laminated Timber	Green Roof Roofing Membrane Bonding Adhesive Straw Bale as Insulator Vapor Control Membrane Primer Concrete

CHAPTER 4

RESULTS

The suggested technique must first be confirmed before it can be used in real-world construction scenarios. A case study from Germany was used as a testing to show how this technique makes it simpler to construct the circular structure, which is covered at the conclusion of the preceding chapter. In Chapter 4, various building circularity indicator data are provided together with five 5R-based design solutions.

The case study was modeled at LOD 300, where the object contains specific numbers, dimensions, shapes, locations, and orientations. The building circularity evaluation needs details regarding quantity, size, shape, location, and orientation. Therefore, in the basic building circularity evaluation during the early design stages, LOD 200 should be the minimal degree of detail. The core model or a symbol is depicted in LOD 100. LOD 400 and LOD 500 designate an application on-site or a particular model that has to be manufactured. By their exact placement, definite amount, and orientation, in addition to other details, they are also helpful in building circularity assessments following construction stages for usage or end-of-life situations. In this thesis, LOD 300 was used in modelling due to case study's being unbuilt design and its certain information of form, orientation, location, quantities and details.

In Chapter 4, visualized results for environmental consequences, recovery indices, and deconstructable elements are shown. Two types of legends are offered to help comprehend the output from BIM models. For environmental effects, recovery indices, and building circularity results, a color range displays the degree of these metrics. Green and anthracite hues for demountability and prefabrication are a result of spread of true/false options .

4.1 Environmental Impact Results

Environmental impact results are based on Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Depletion Potential (ODP) with respect to different phases. In A module, raw material extraction, transport, manufacturing, and installation processes are held. Use and maintenance of a product are the subject of the B module of LCA. Deconstruction, waste operations, including transportation, processing, and disposal are covered in module C. Module D refers to the reuse, recovery, and recycling potentials of the material. Product (A), end-of-life (C), and benefits beyond-the-system (D) stages are considered in all impact categories except ODP. In ODP, there is insufficient data for the D module to use in the study. Therefore, ODP was calculated in A and C modules. Use stage (B) is negligent in these results since environmental impacts cannot be derived easily in the phase.

In EPDs and different types of material passports, the environmental impact results of a single product can be found. These results were applied in BIM environment and calculated according to the quantity and service life of the product in Dynamo. To calculate the environmental impact index among the project elements, Eq. 6 was used. Then, these results are scaled between 0-1 to grade impacts by colors below the paragraph.

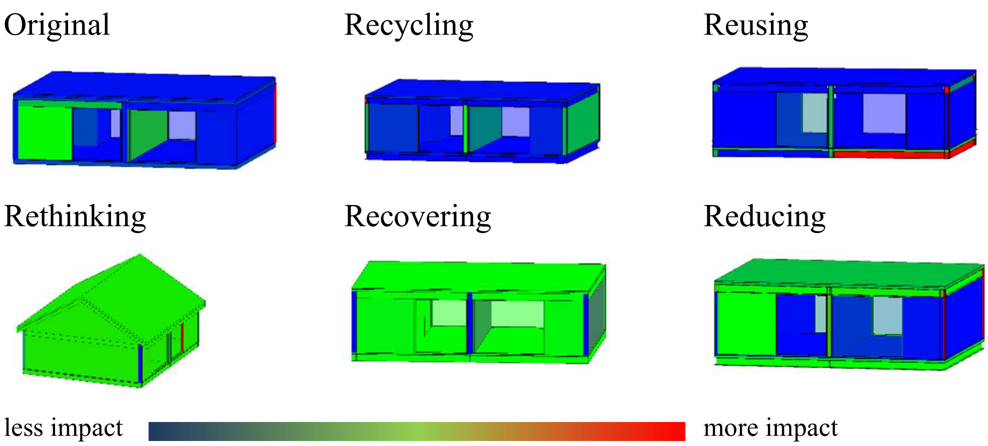

Figure 4.1. GWP results in A module of design alternatives

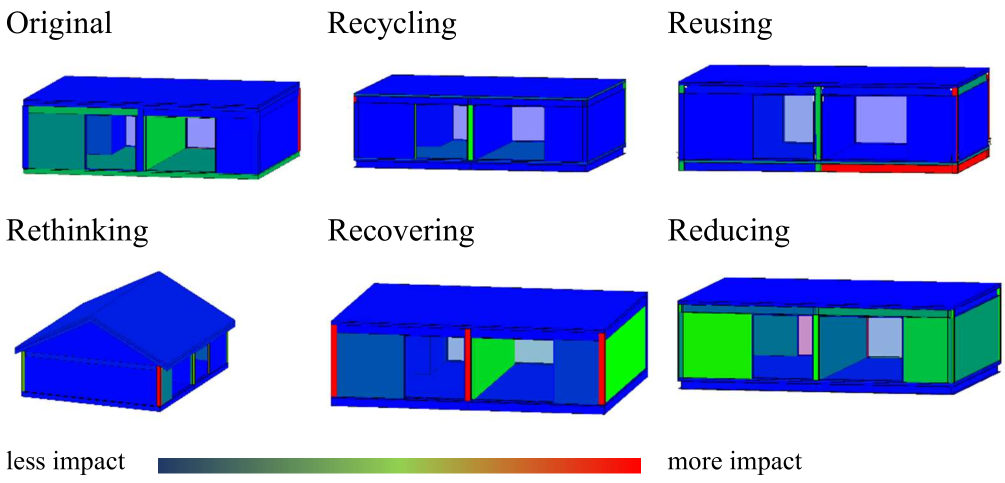

Figure 4.2. GWP results in C module of design alternatives

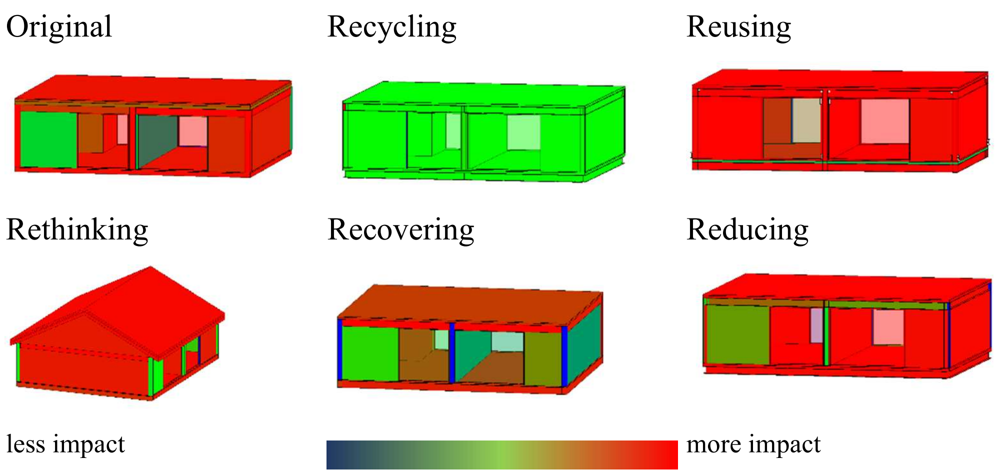

Figure 4.3. GWP results in D module of design alternatives

Visuals of GWP results show that insulated concrete sandwich walls and columns become the least sustainable material among all components. In C module, walls have a noticeable effect on global warming when other materials have very small impacts except in Reusing and Recycling. Most heterogenous contribution to global warming is also observed in C module. Due to shortage of logical environmental results in D module of a few elements such as curtain walls and columns, most of the elemetns are shown in red color, which implies more impact although these elements do not contribute global warming severely.

To compare the environmental impacts of the alternatives, Table 4.1. assists as a digital dataset. According to Table 4.1., original design has the most contribution to GWP, since any circularity principles are not implicated in this design. Rethinking alternative impacts global warming the least among the design alternatives.

In terms of global warming potential, Recovering and Rethinking alternatives are more appealing than Reusing and Recycling. Although components in Reusing and Recycling alternatives are designed to beyond end-of-life uses, original structure has less contribution to global warming potential. The impact of Reusing almost averages all alternatives.

Table 4.1. GWP of design alternatives

Design Alternatives	**Module A (kg CO2 eq.)**	**Module C (kg CO2 eq.)**	**Module D (kg CO2 eq.)**	**Sum (kg CO2 eq.)**
Original	152264.86	10523.63	-15196.53	**147591.96**
Recycling	79586.89	4699.49	-908.88	**83377.5**
Reusing*	26655.24	17474.1	-106.24	**44023.1**
Rethinking	-66175.43	163493.81	-126295.1	**-28976.72**
Recovering	-164973.46	255598.07	-101660.81	**-11036.2**
Reducing	424934.63	91187.05	-408015.26	**108106.42**
*Useful life of Reusing is 60 years, while others are 40 years. Therefore, the results are normalized to 40 years.				

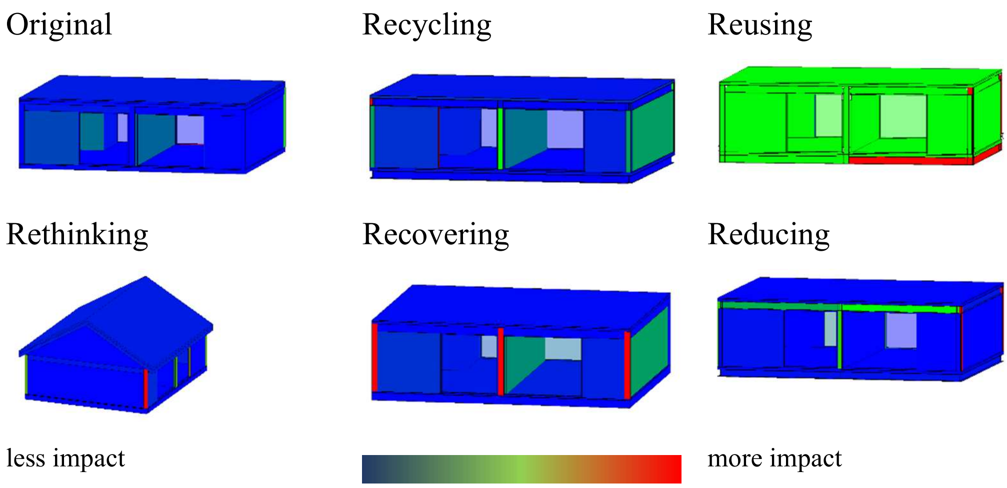

Figure 4.4. AP results in A module of design alternatives

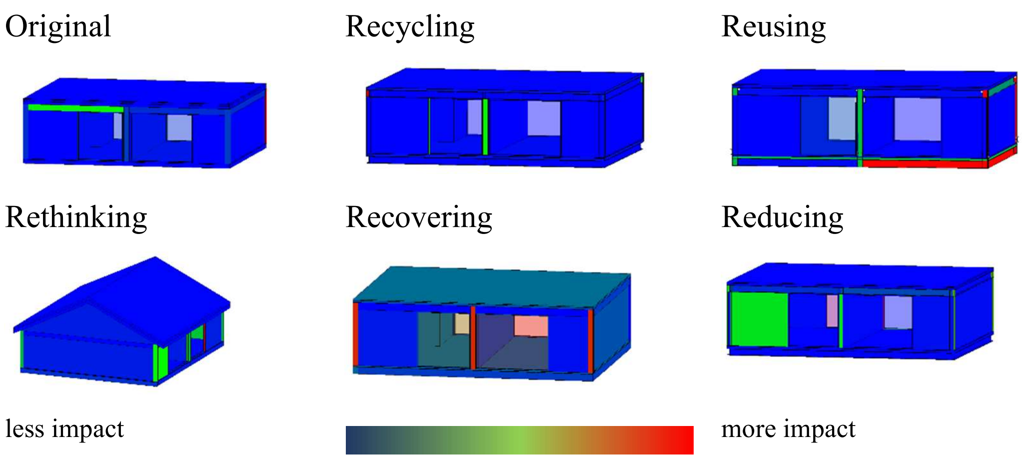

Figure 4.5. AP results in C module of design alternatives

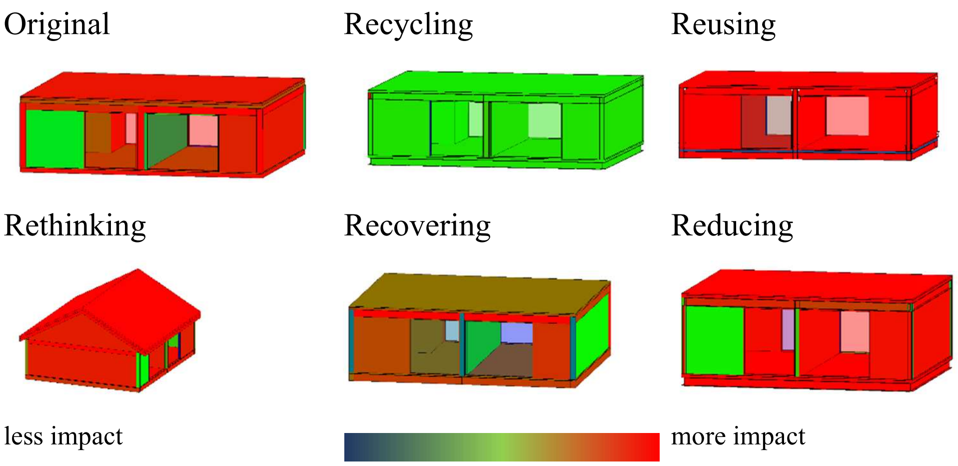

Figure 4.6. AP results in D module of design alternatives

According to AP results, insulated sandwich walls, columns and beams have the most contribution on Acidification Potential in A module in almost all design alternatives. In Reusing alternative, all construction elements impact almost equally on acidification in A module. In C module, timber frame and steel structures have the most impact on global warming. Majority of components including walls, roofs, and flooring significantly contribute to AP in D module.

According to Table 4.2., original design has overwhelmingly most contribution on Acidification than other alternatives, when Rethinking has the least impact. Acidification potential has negative values in Rethinking and Reducing alternatives. Reusing and Recovering alternatives are closely resulted in terms of Acidification.

Table 4.2. AP of design alternatives

Design Alternatives	Module A (mol H+ eq.)	Module C (mol H+ eq.)	Module D (mol H+ eq.)	Sum (mol H+ eq.)
Original	4677.89	9459.39	-120.82	**14016.46**
Recycling	491.98	36.74	-38.21	**490.51**
Reusing*	72.47	99.69	-0.61	**171.55**
Rethinking	403.15	64.84	-618	**-150.01**
Recovering	572.75	32.08	-314.29	**290.54**
Reducing	1289.48	151.22	-1476.88	**-36.18**
*Useful life of Reusing is 60 years, while others are 40 years. Therefore, the results are normalized to 40 years.				

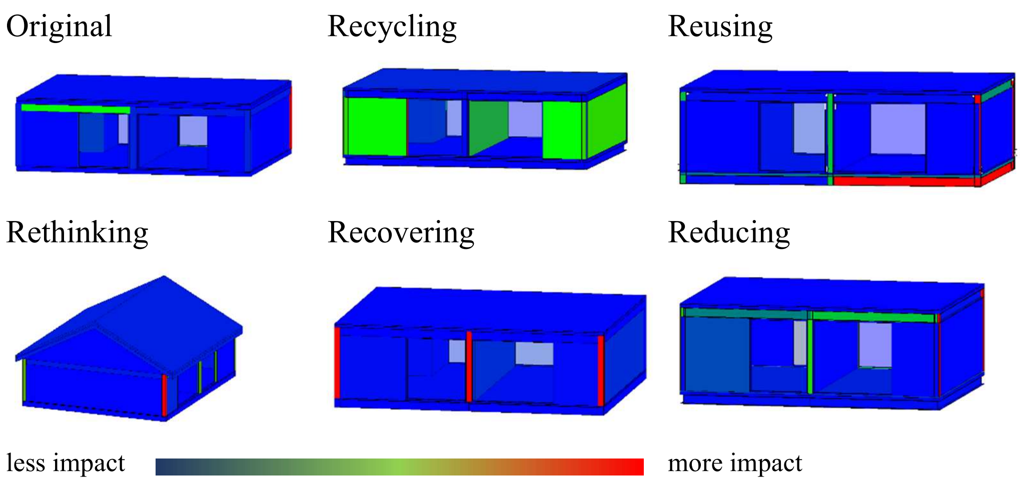

Figure 4.7. EP results in A module of design alternatives

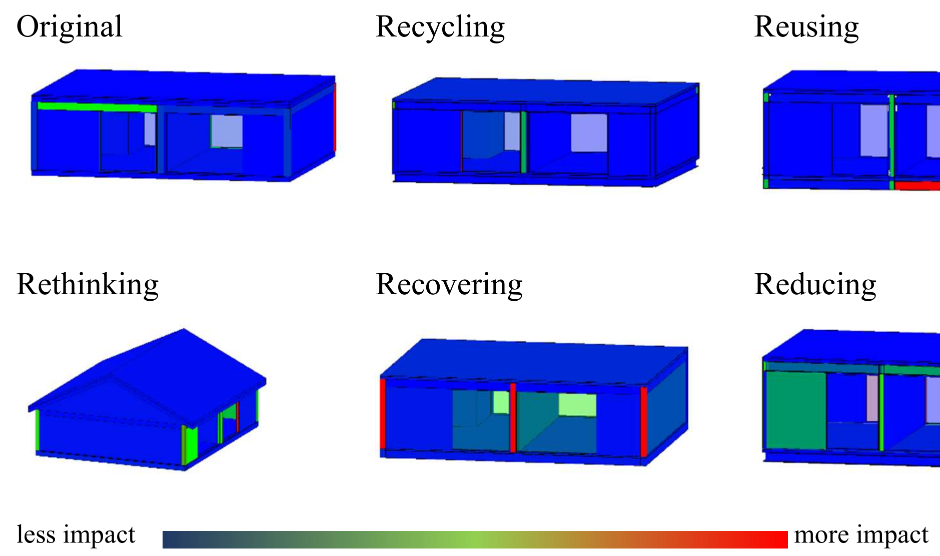

Figure 4.8. EP results in C module of design alternatives

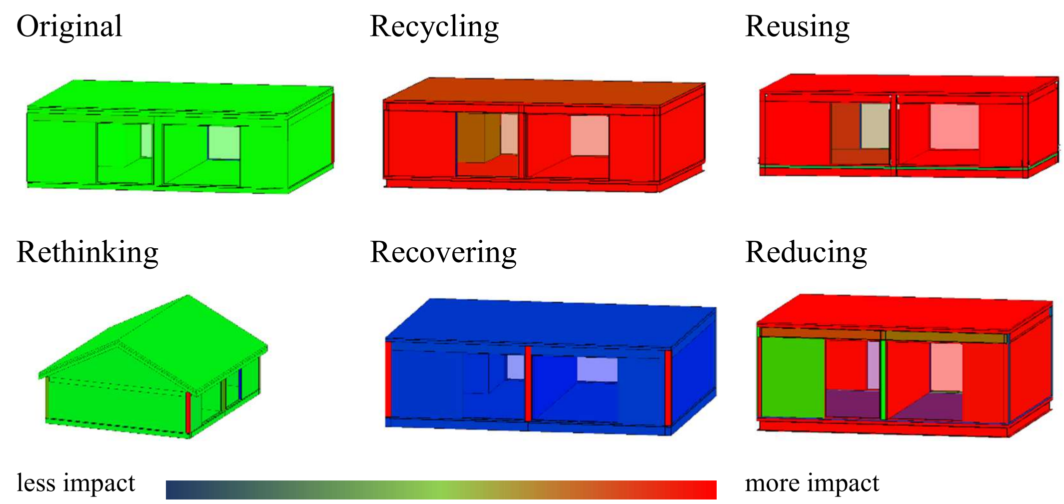

Figure 4.9. EP results in D module of design alternatives

The EP result visuals indicate that walls, columns and beams have the most impact on eutrophication in module A and C. However, in module D, walls, floors and roof structures contributes it mostly except in Recovering alternative. In Recovering alternative, Eutrophication potential is significantly high in columns. In original and

Rethinking alternatives, majority of design elements have almost same contribution on Eutrophication.

Table 4.3. implies that all design alternatives have close results except original. EP values of original design are 2-100 times higher than other design alternatives. There is no negative impact on Eutrophication in any design alternative. Despite many sustainable technologies in Rethinking or more environmentally friendly materials etc., any design strategies are not enough to reduce the eutrophication potential into negative values.

Table 4.3. EP of design alternatives

Design Alternatives	**Module A (kg PO4 eq.)**	**Module C (kg PO4 eq.)**	**Module D (kg PO4 eq.)**	**Sum (kg PO4 eq.)**
Original	1051.18	90.34	-29.75	**1111.77**
Recycling	523.02	8.42	-85.74	**445.7**
Reusing*	19.48	18.74	-0.05	**38.17**
Rethinking	148.4	2.07	69.78	**220.25**
Recovering	206.66	1.79	158.71	**367.16**
Reducing	90.82	4.78	-54.98	**40.62**
*Useful life of Reusing is 60 years, while others are 40 years. Therefore, the results are normalized to 40 years.				

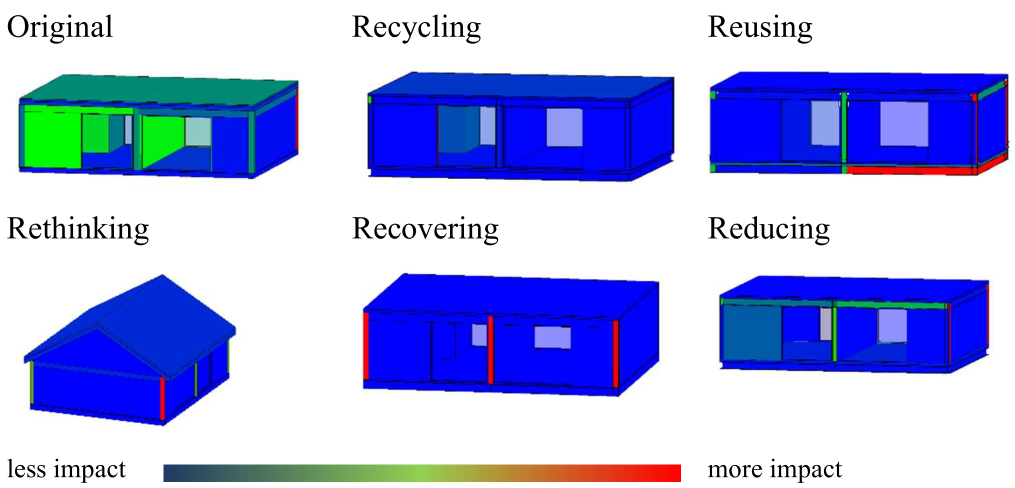

Figure 4.10. ODP results in A module of design alternatives

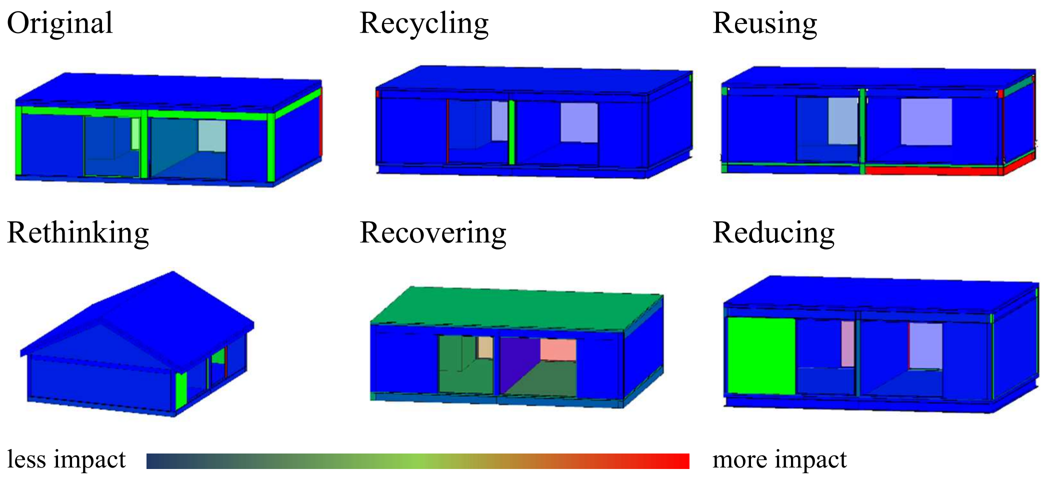

Figure 4.11. ODP results in C module of design alternatives

Due to insufficient datasets, D module results cannot be retrieved through the Dynamo scripts. Walls of original and Reducing alternatives have the most effects on ozone depletion potential, according to these results, while columns and beams contributes most in other alternatives. ODP results also indicate that Reusing alternative has no impact on Ozone Depletion.

Table 4.4. indicates that all design alternatives have very little effect on ozone depletion potential. Every alternatives change in only one thousandth values.

However, Recovering doubles the ODP results, since its elements are planned to be burned and produce heat energy after end of life. Aftermath of the incineration of these elements detriments ozone layer due to produced gases. On the other side, Reusing and Reducing have the lowest impact on ozone depletion potential among 5R strategies. In other words, Reusing and Reducing alternative is advantageous in impact on ozone depletion potential.

Table 4.4. ODP of design alternatives

Design Alternatives	**Module A** (kg CFC 11 eq.)	**Module C** (kg CFC 11 eq.)	**Sum** (kg CFC 11 eq.)
Original	0.12	0.14	**0.26**
Recycling	0.15	0	**0.15**
Reusing*	0	0	**0**
Rethinking	58.1	0	**58.1**
Recovering	110.65	0	**110.65**
Reducing	0.01	0	**0.01**
*Useful life of Reusing is 60 years, while others are 40 years. Therefore, the results are normalized to 40 years.			

4.2 Recovery Results

The linear flow index, potential recycling, and reuse indices of Mesa et al. are the basis of the recovery score (2018). Three tables with various recovery indices are produced by averaging these indexes. Utilizing recycled and used materials throughout the manufacturing and being able to reuse and recycle them at the end of their useful lives are crucial considerations when calculating these values.

To calculate recovery results, output flows and resource uses were beneficial to define the required information for Equation 1,2 and 3. Moreover, Equation 5 was used to create an averaged index for assess recovery potential of products. These formulas were transferred in Dynamo environment and scaled into a range between 0-1 to grade components by these colors.

In order to adjust these indices, 5 R strategies propose various production and end-of-life scenarios. Potential reuse index has the most value in the Reuse option, while potential recycle index is unquestionably more prevalent in the Recycling alternative.

More Linear Flow Index means less circularity in the project. In majority of these design options, exterior walls have the lowest linear flow index, while floors and roofs get the highest. It means that floor and roof structure are less circular, when exterior walls are more circular. According to the linear flow index, these materials diminish the circularity of the structure since they cannot accomplish the next life cycle.

Rethinking is the least recyclable option out of the study's five R's, according to potential recycle index graphics, because the elements in Rethinking alternative is planned to be reused or incinerated rather than recycling after end of life. Since original design is not designed with any circular economy principles, original design is the least reusable option.

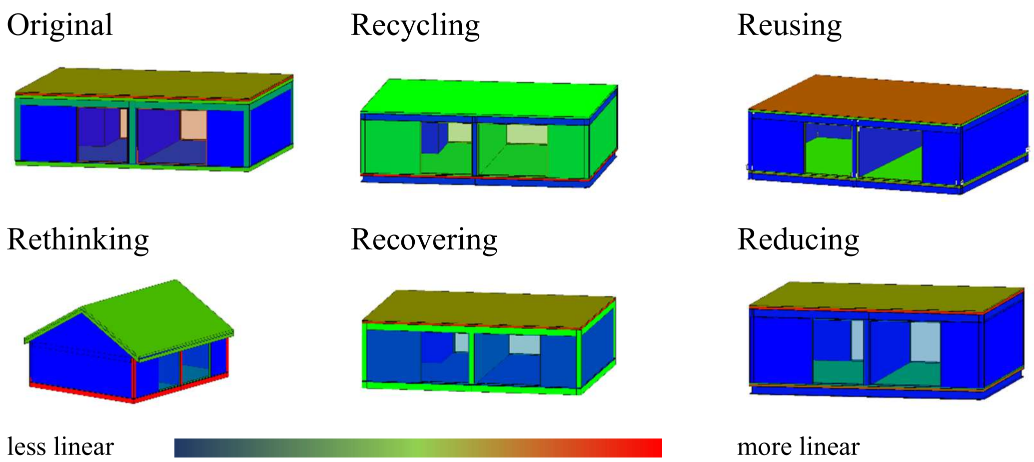

Figure 4.12. Linear Flow Index of design alternatives

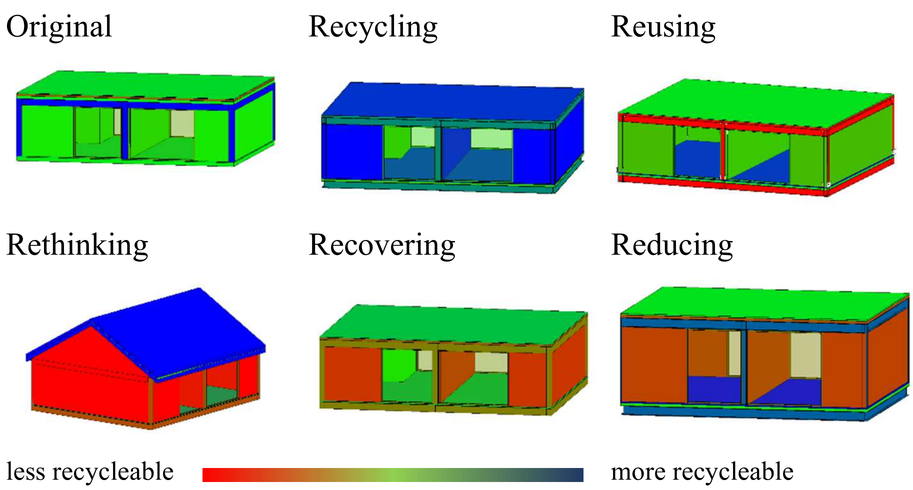

Figure 4.13. Potential Recycle Index of design alternatives

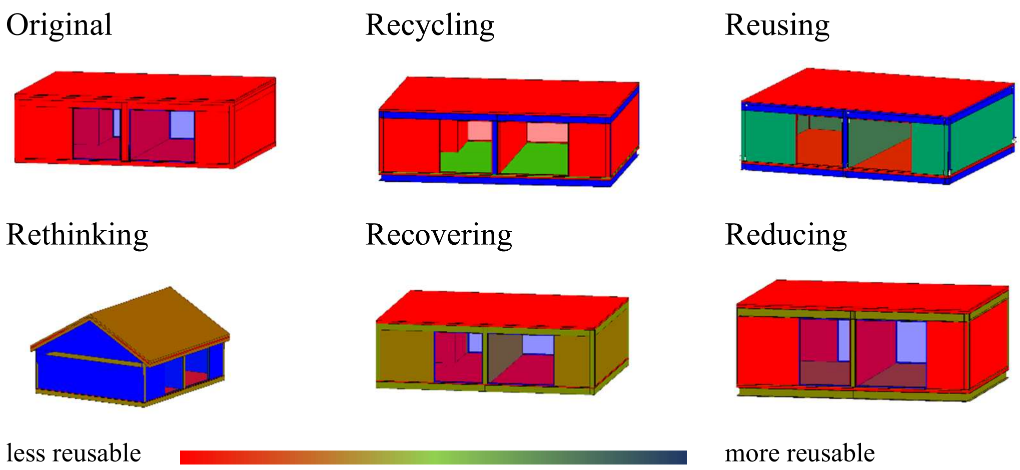

Figure 4.14. Potential Reuse Index of design alternatives

Table 4.5. Recoverability Score

Design Alternatives	**Recoverabilty Index**
Original	0.28
Recycling	0.39
Reusing	0.45
Rethinking	0.41
Recovering	0.36
Reducing	0.46

4.3 Deconstruction Results

Based on Atta et al.'s formulation of Deconstructability score (2021) (Eq. 4), construction elements were sorted into demountability and prefabrication. True/false booleans in Dynamo are important in defining the number of prefabricated or demountable elements to apply Eq.4. Number of elements to demount or prefabricate were used to find deconstructability score and show which elements can be demountable or prefabricated or not. Answers for whether they can be deconstructable were gathered from material EPDs and end of life scenarios of design alternatives. Therefore, true/false booleans becomes the basis element for the creation of these figures below (see Figure 4.15-16).

The majority of demountable and prefabricated components may be found in the Reusing, Rethinking, and Recovering choices since the design for deconstruction approach is suggested in these options. Additionally, the Reducing option, which is based on a lighter framework, has a considerable proportion of prefabricated and demountable components in comparison to all other construction materials. When employing materials from one structure after it has reached the end of its useful life in another, or when recovering energy from these materials, ease of deconstruction is crucial. In other words, all 5R alternatives except original design have close deconstructability values, which means that they can be deconstructable more easily than the original.

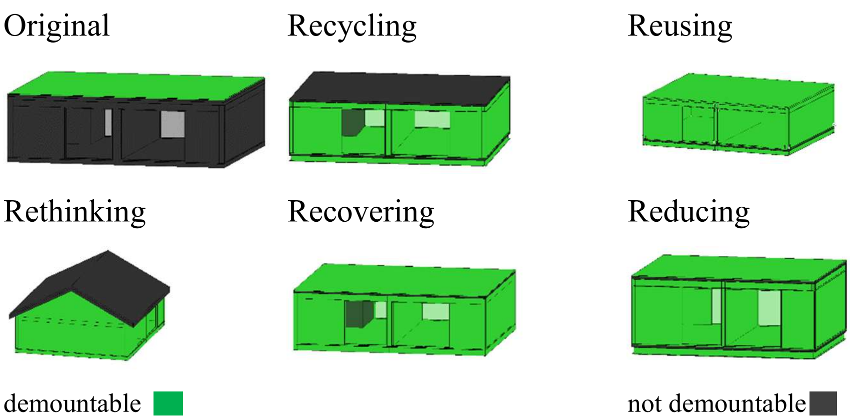

Figure 4.15. Demountability

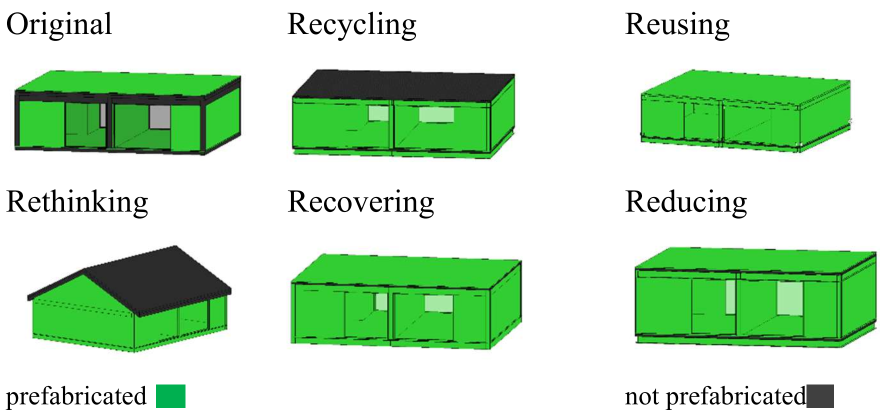

Figure 4.16. Prefabrication

Table 4.6. Deconstruction Score

Design Alternatives	**Deconstructabilty Index**
Original	0.13
Recycling	0.9
Reusing	0.93
Rethinking	0.96
Recovering	0.92
Reducing	0.92

4.4 Building Circularity Results

Building circularity score was determined for a whole building rather than component by component as prior metrics had done. It was based on an average of recovery score, deconstructability score, and environmental impact score. The original structure does not imply any retention choices, hence its construction circularity score result is the lowest of the five R methods. Reusing, Rethinking, Reducing and Recovering belong very close circularity results whose values change in 0.12 points, in spite of their difference in structure and orientation.

Rethinking has the most contribution to building circularity results with 0.59 points, since environmentally friendly technologies and other circular design strategies are combined in this alternative.

Although the structure of Reducing alternative changed by only making it more lightweight, Reducing becomes the second most circular design alternative among 5R strategies.

By replaceable building components, less environmental impacts with lightweight construction, higher deconstructability and durability are inevitable factors in production and construction stages. As a result, they bring about appealing building circularity scores to Rethinking strategy in construction.

Table 4.7. Building Circularity Score

Design Alternatives	**Building Circularity Index**
Original	0.15
Recycling	0.47
Reusing	0.54
Rethinking	0.59
Recovering	0.49
Reducing	0.56

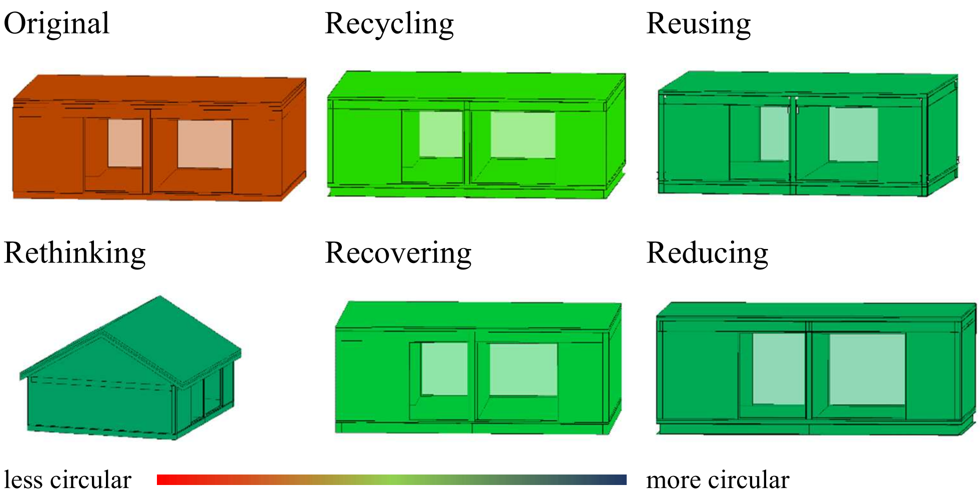

Figure 4.17. Building Circularity Score

4.5 Discussions

The framework should be adopted to various types of projects in different scales, location, structure types or functions. Since the Dynamo codes are common to all Revit models, the calculation part of circularity indices and scores can be conducted. However, needed parameters such as deconstructability, environmental impacts and potential reuse index, and EPDs passports of the model elements have to be entered into the BIM environment before the calculations. Environmental Product Declarations can be found for different construction components or MEP fixtures, such as electrical or mechanical installations. In other words, environmental information about all model elements which are gathered from EPDs are provided for different types and functions of components. Calculations in Dynamo codes can be utilized for all types of elements in a construction model.

A real time usage of the framework was exemplified below the paragraph. The real project is a mixed-use complex in Ordu, Turkey, which is at the beginning construction phase in 2023. It comprises 3 storeys of retail, 6 storeys of offices and residences as an urban improvement project. The project is chosen to demonstrate the application of the framework in a real project, since case study was cancelled to be built in Germany.

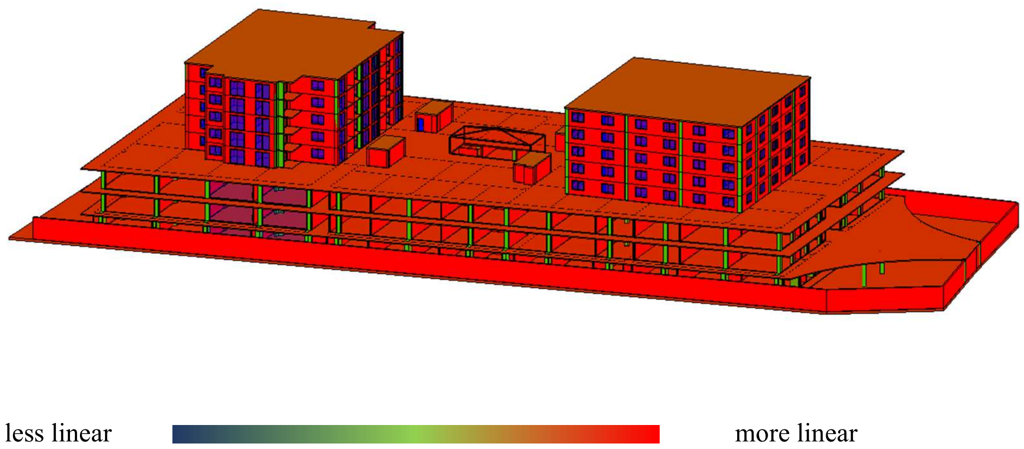

Figure 4.18. Linear Flow Index of sample mixed-use project in Ordu

In Figure 4.18., the linear flow index of construction materials in the project were calculated. How linear are the construction components can be understandable from the visual. Red elements reduce the circularity indices of the project, when blue ones make it more circular. Since the building was built of reinforced concrete structure and large scaled project without consideration of any end-of-life scenario. Its circularity indices are highly detrimental for environment. In Turkey, there is limitation of specific EPDs for construction elements. Hence, generic EPDs are used to extract environmental information about the construction elements.

The second example project is also from Ordu, Turkey. The project is at the middle of the construction phase. It will function as a residential building with its 5 floors. The building was chosen to indicate the real implication with mechanical, electrical and plumbing (MEP) installations.

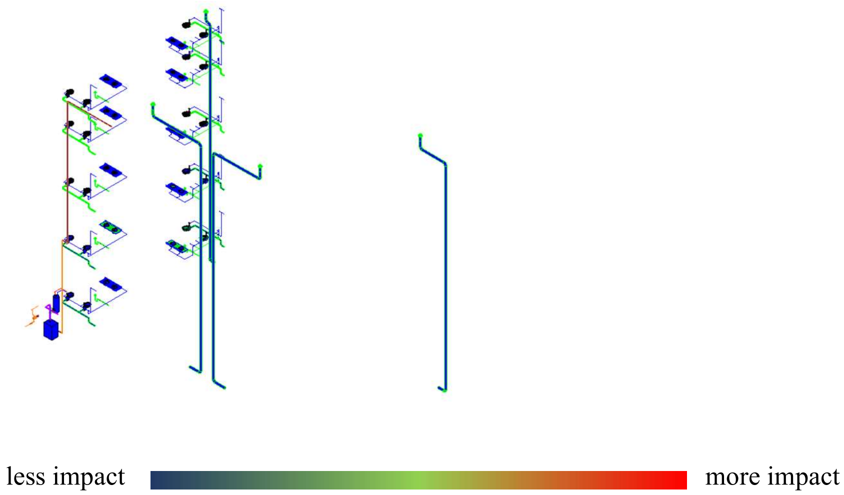

Figure 4.19. Global Warming Potential of sample MEP project

Figure 4.19. shows the Global Warming Potential of an MEP part of a residential project. Pipes that are not connected to pump and plumbing equipments are more environmentally friendly in terms of Global Warming Potential, while pump and connected pipes contributes it more. Many circularity indicators such as Global Warming Potential, Linear Flow Index or Demountability can be measureable and graphically displayed for various types and scales of projects in terms of Architectural, Structural or MEP sides of it. However, there are insufficient amounts of EPDs for MEP equipments such as boilers or water heaters. Therefore, if these EPDs are conducted accurately and more widespread, the framework becomes more plausible for also MEP projects.

CHAPTER 5

CONCLUSION

Building circularity must be visible to promote the transition of the construction sector from a linear economy to a circular economy. As a component of global sustainability efforts toward a circular economy, this study provides a workflow to evaluate building circularity by presenting visually graded circularity findings in a BIM context. The tool is digitally mastered using Autodesk Revit® to benefit from BIM technology's automation, data storage, sharing capabilities, customization, and depiction of this environmental data. Three different types of indicators are needed to carry out the assessment procedure. The first type of indicators is based on the environmental impacts of the building components and materials. They are derived from Environmental Product Declarations of manufacturers' items. The environmental impacts are displayed with production (A), waste processing (C), and beyond-the-life (D) modules of LCA to understand the difference of dominant element that impacts the environment by life cycle phases. The deconstructability, recovery, and environmental scores are incorporated in the second type of indicators that are produced using formulations from studies by Mesa et al. (2018), and Atta et al. (2021). Deconstruction score includes Demountability and Prefabrication indexes. Recovery score, the third type of indicator, is divided into three parts: Linear Flow Index, Potential Recycle Index, and Potential Reuse Index.

Using a case study of a commercial building, the BIM-based visually aided building circularity evaluation tool is examined and verified. The case comprises five design options based on the R-strategies: recycling, reusing, rethinking, recovering, and reducing. These design alternatives are meant to give a decision-making framework for integrating circular economy methods in the early design and end-of-life stages.

Building components must be replaceable or reused after their service life by taking into account better deconstructability, less environmental effect through lightweight construction, and durability. These factors must be taken into account during the manufacturing and construction phases. According to the findings, options that include rethinking and reusing have the finest deconstruction and recovery capabilities and have the least detrimental effects on the environment. Moreover, Rethinking alternative comprises of two rooms designed as open plan system to fit any function or needs into the design. Hence, they have the most recoverable (recycle, reuse or recover), light-weight, and destructible components, earning them the highest circularity rating. After making building materials more lightweight and adaptable in the Reducing option, the circularity scores were notably different from the original design. Since no circular retention alternatives are used during construction, the building circularity findings are the lowest in the original design of the five R strategies.

The indications for the instances under examination result in comprehensible conclusions, proving the utility of the circularity evaluation paradigm put forward in this thesis. By displaying the findings of each indicator graphically, this thesis helps to evaluate the circularity indicator. These illustrations assist in determining the components that contribute to environmental effects, recovery, or deconstruction. The overall circularity score is determined by averaging the results of various equations, as shown in these pictures. The score is also represented so that you may compare various design options or gauge how circular the project is. Therefore, by graphically showing the results of circularity evaluations, the recommended tool aids non-specialists in their decision-making. To demonstrate the practical use of the framework, two large-scale mixed-use projects—one in Ordu, Turkey, under construction—and a plumbing project for a residential building were used. The framework can efficiently analyze circularity for many different sorts of projects in addition to case study projects, as shown by sample visual findings in the Discussion section.

Although this tool gives visual results for the circularity evaluation, environmental information in operation phase and end-of-life scenarios are not defined accurate enough to achieve more precise results and it limits the spectrum of utilizable materials in the design. For instance, current EPDs are not sufficient for many types of components such as MEP equipments. Hence, all construction and MEP components should have an accurate EPD to reduce these limitations. Moreover, the framework does not consider the use and repair processes of these buildings due to insufficient datasets of products in Use and Maintenance Stage. More studies about building circularity in Use and Maintenance stage are also required for future works to reduce the limitation.

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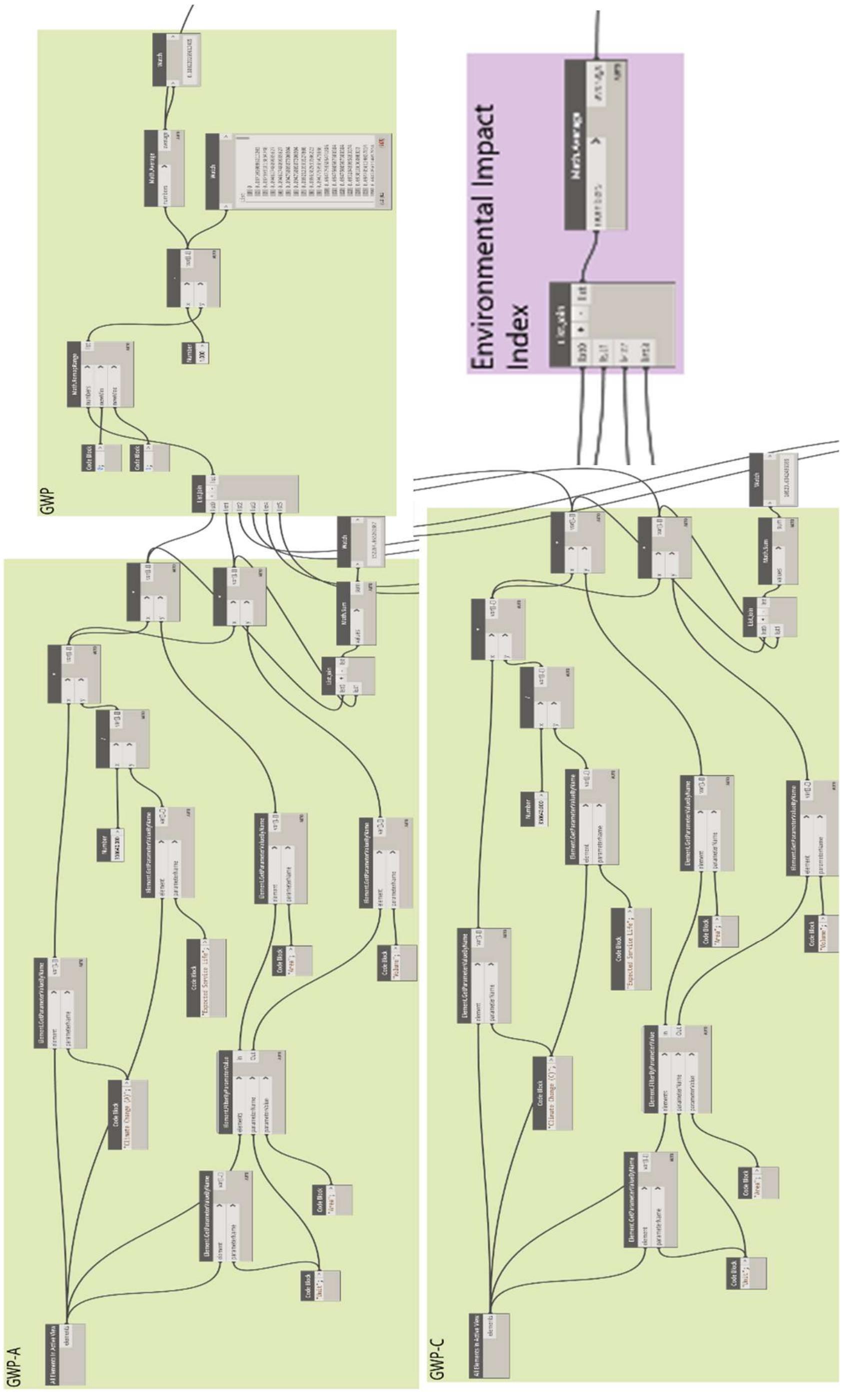
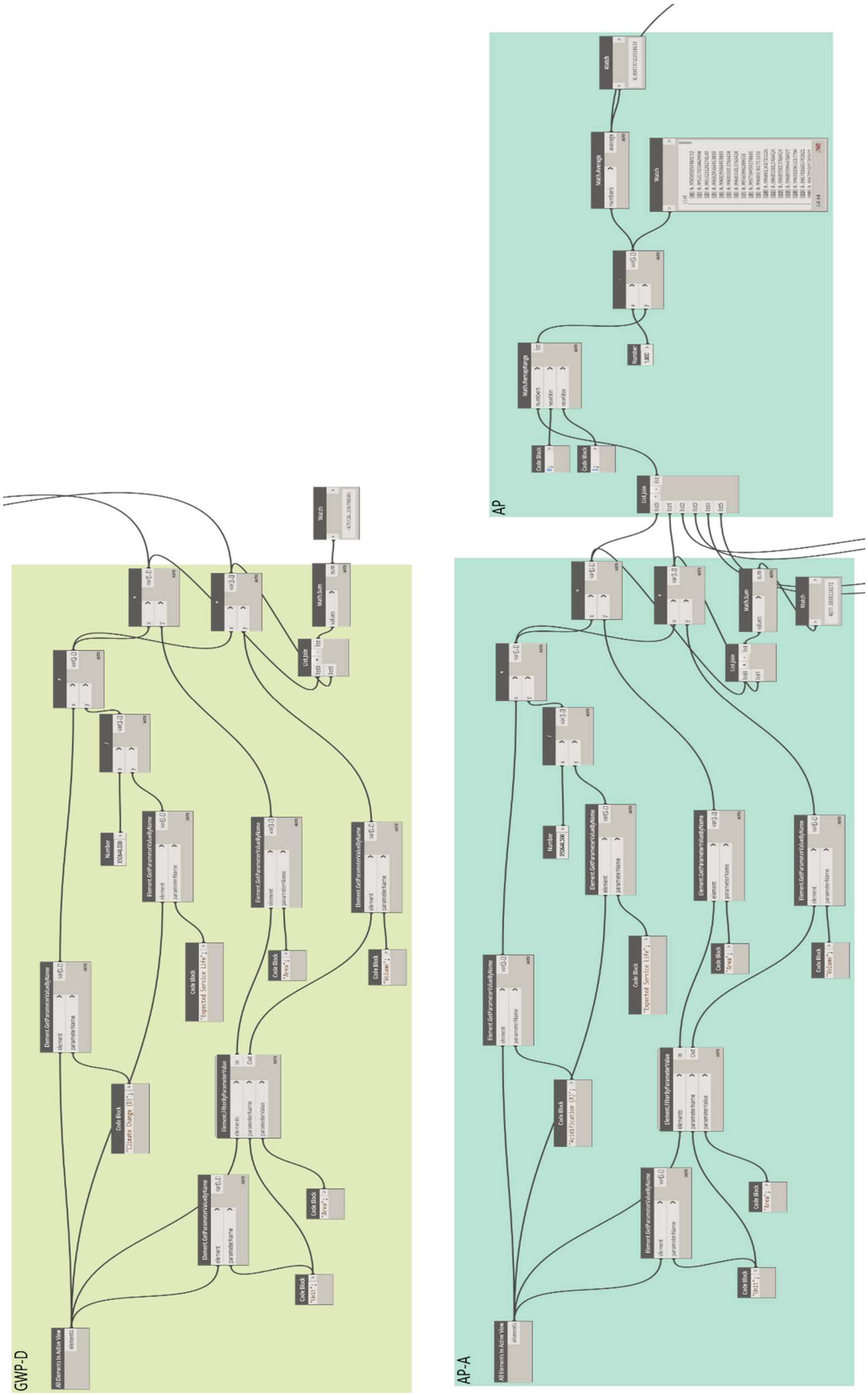
APPENDICES

A. Dynamo Scripts

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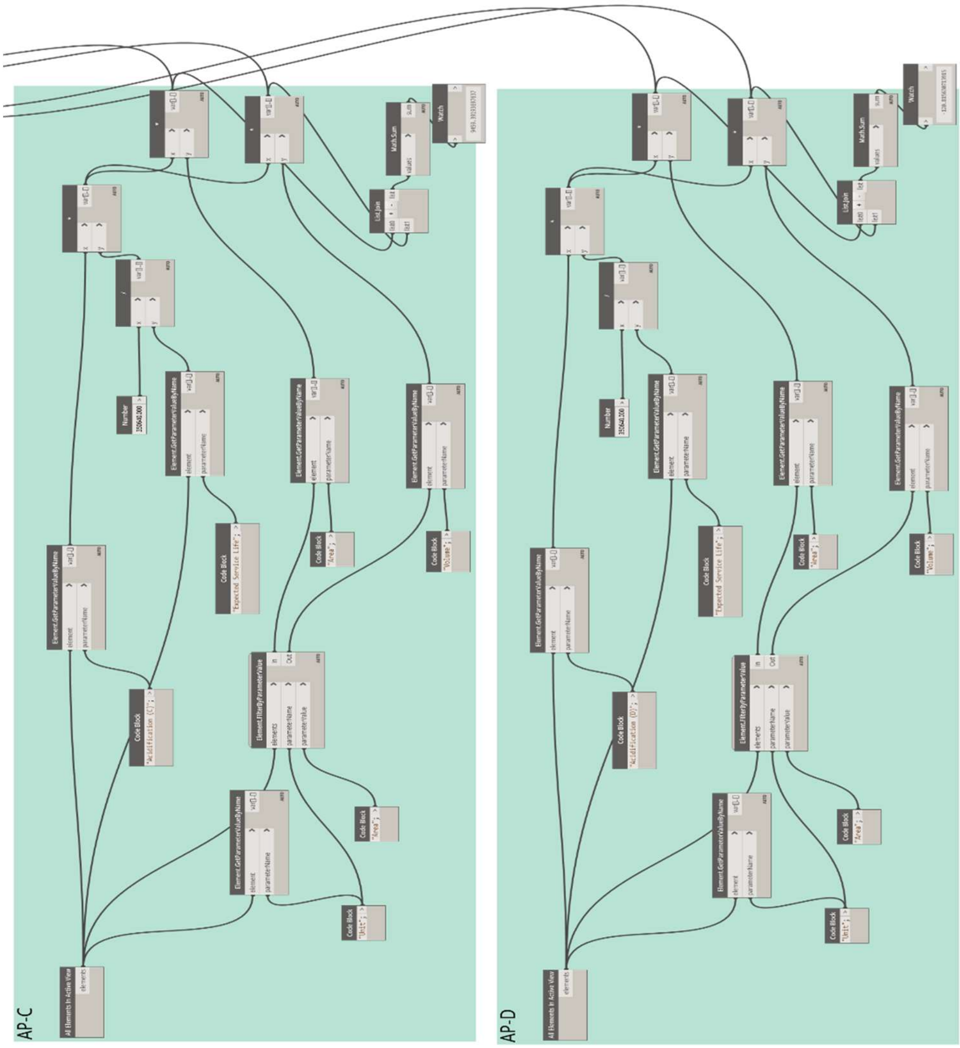
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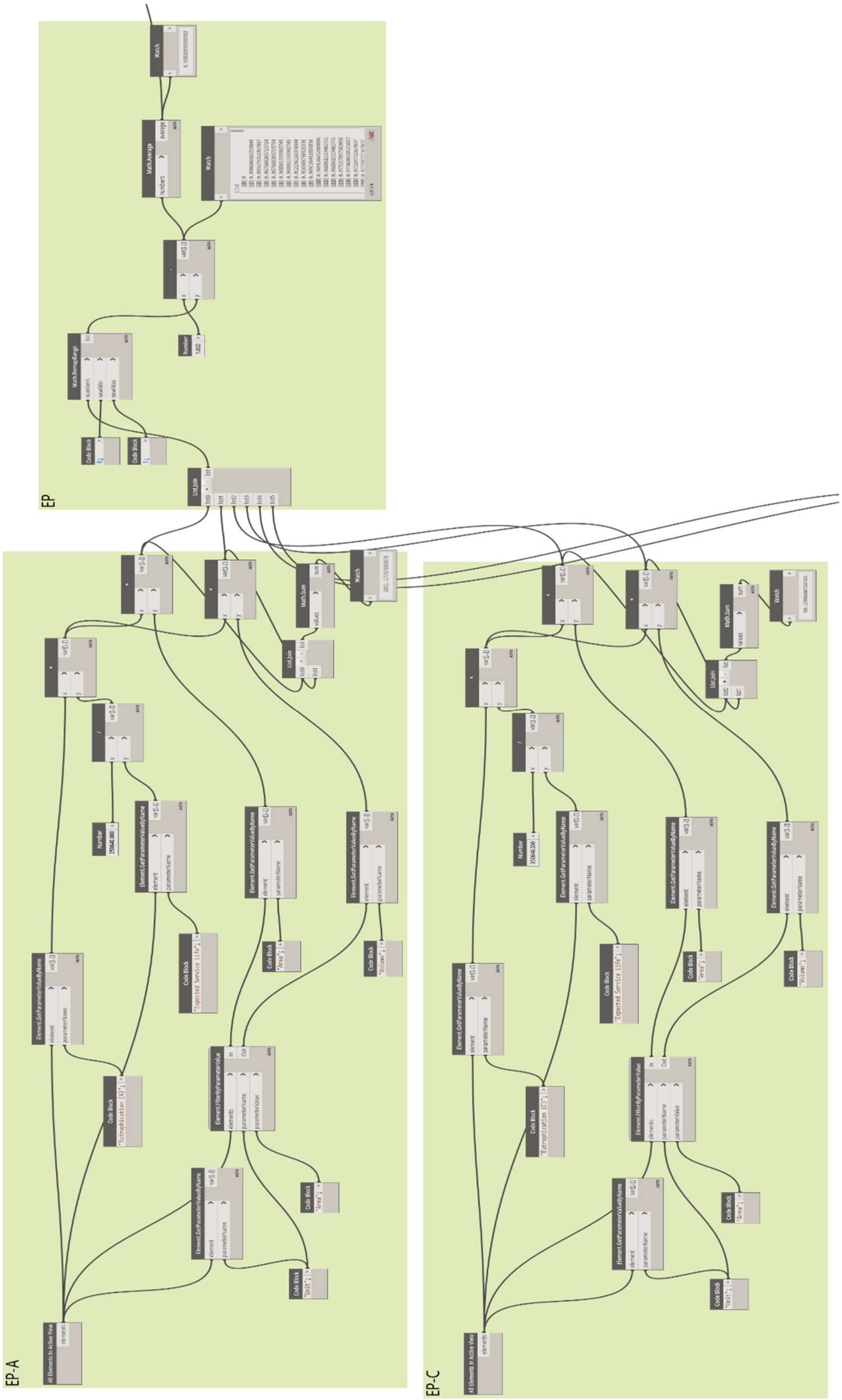
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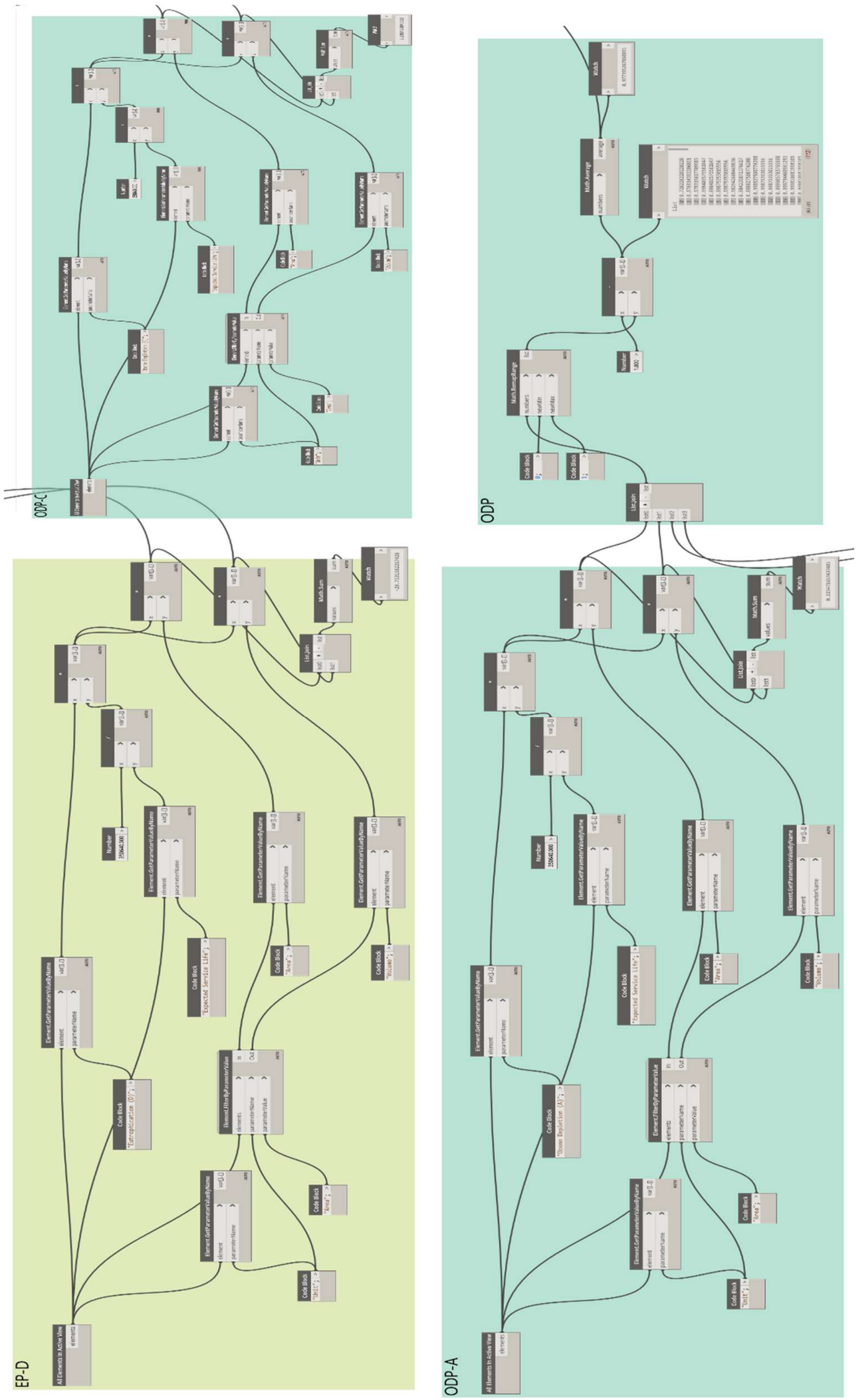
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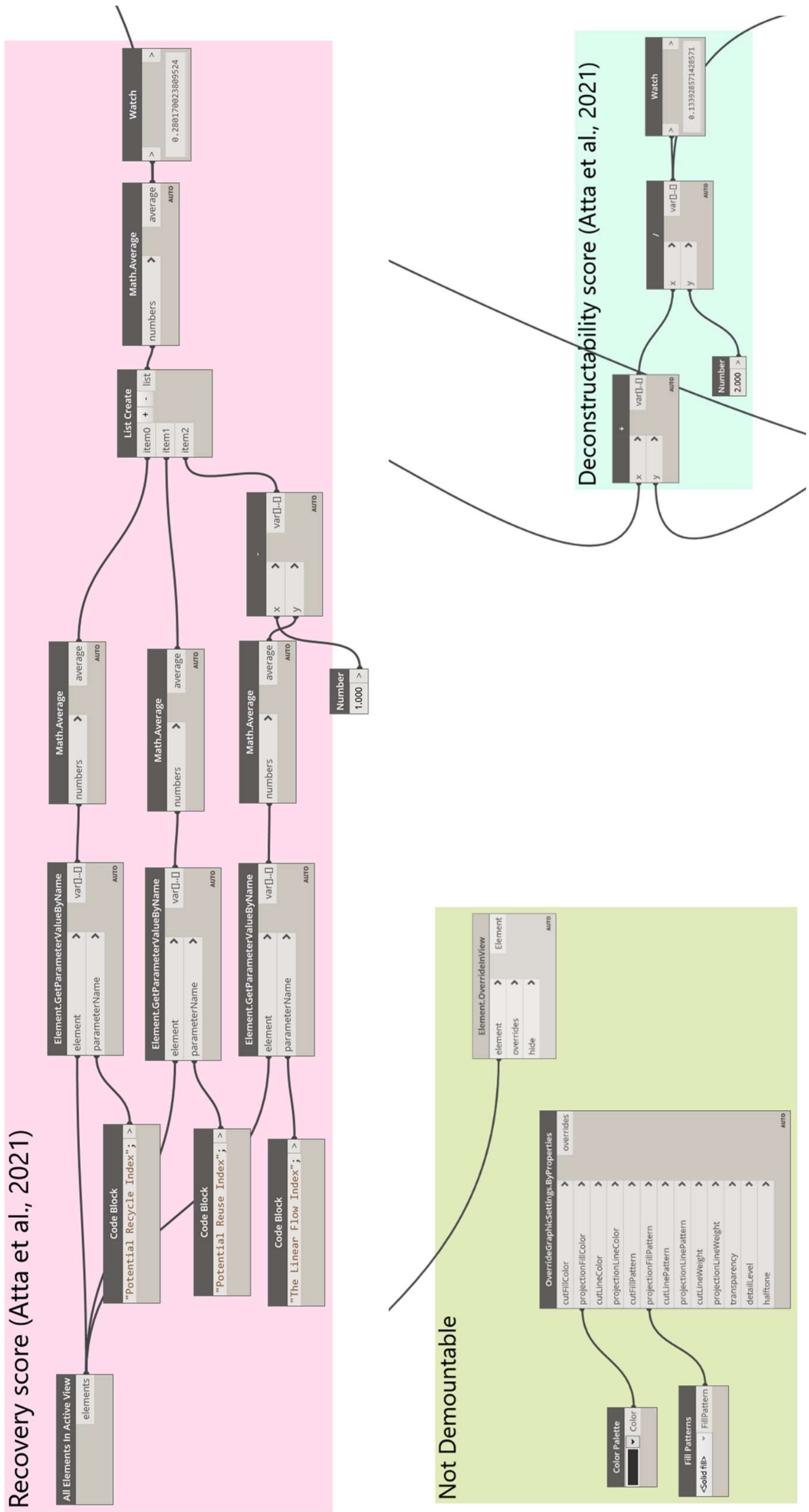
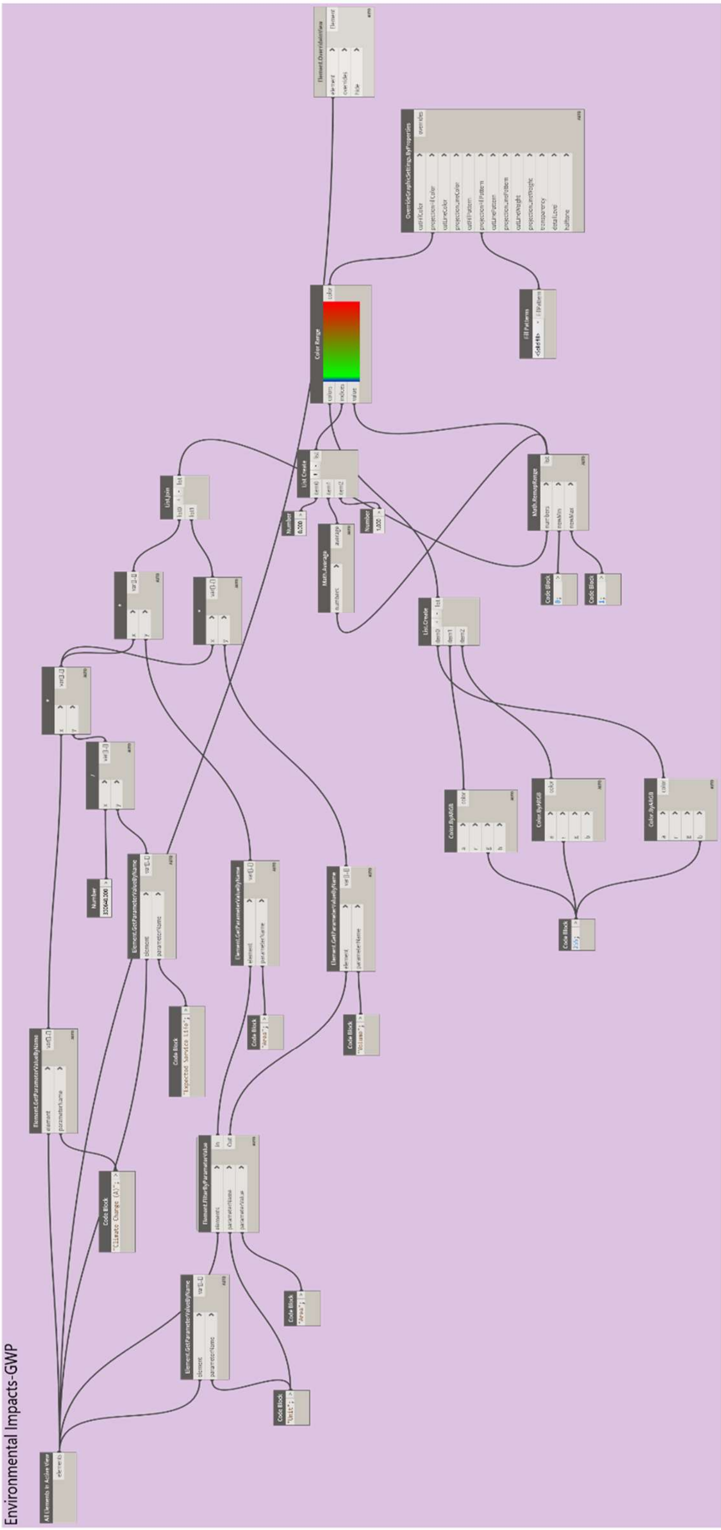
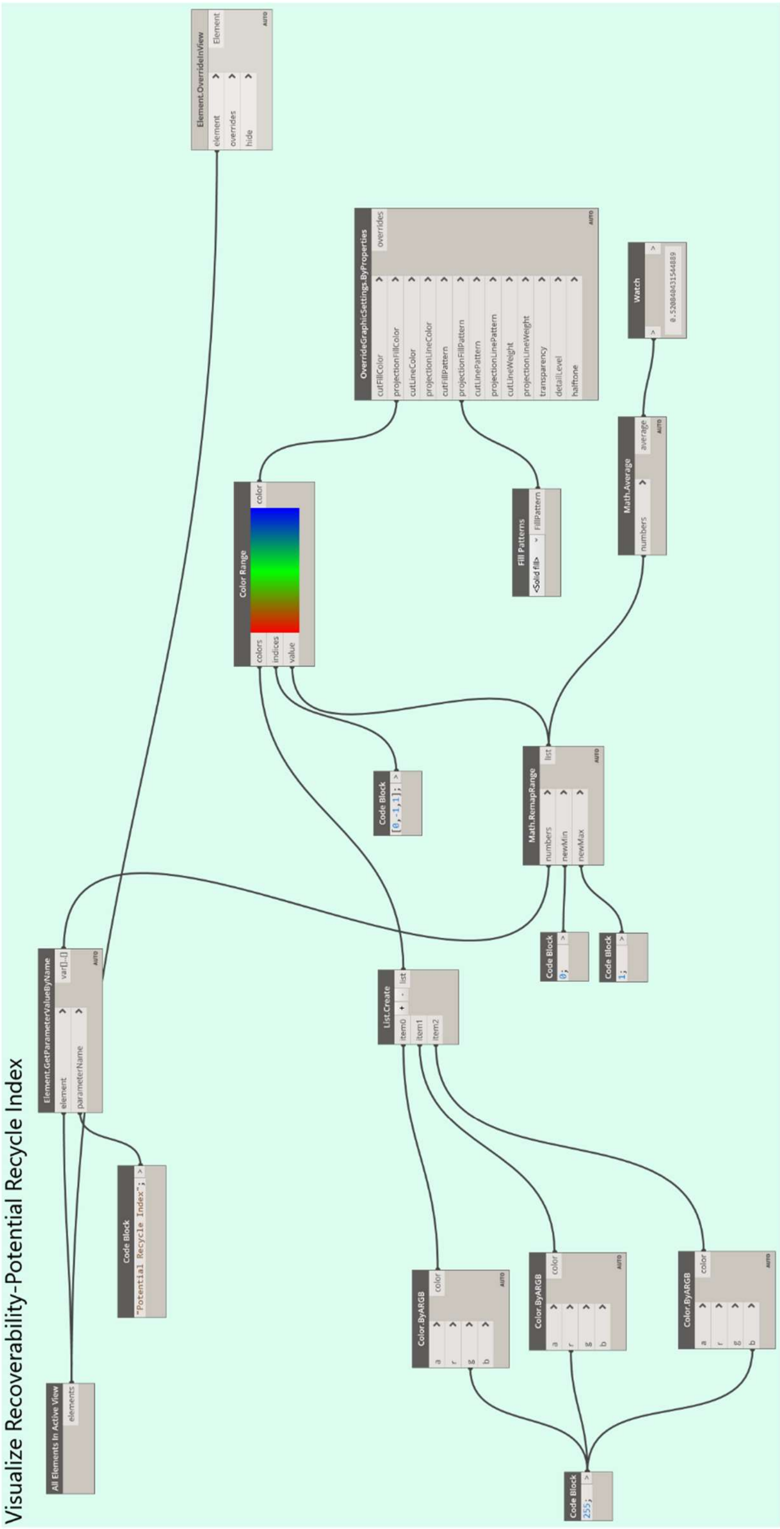
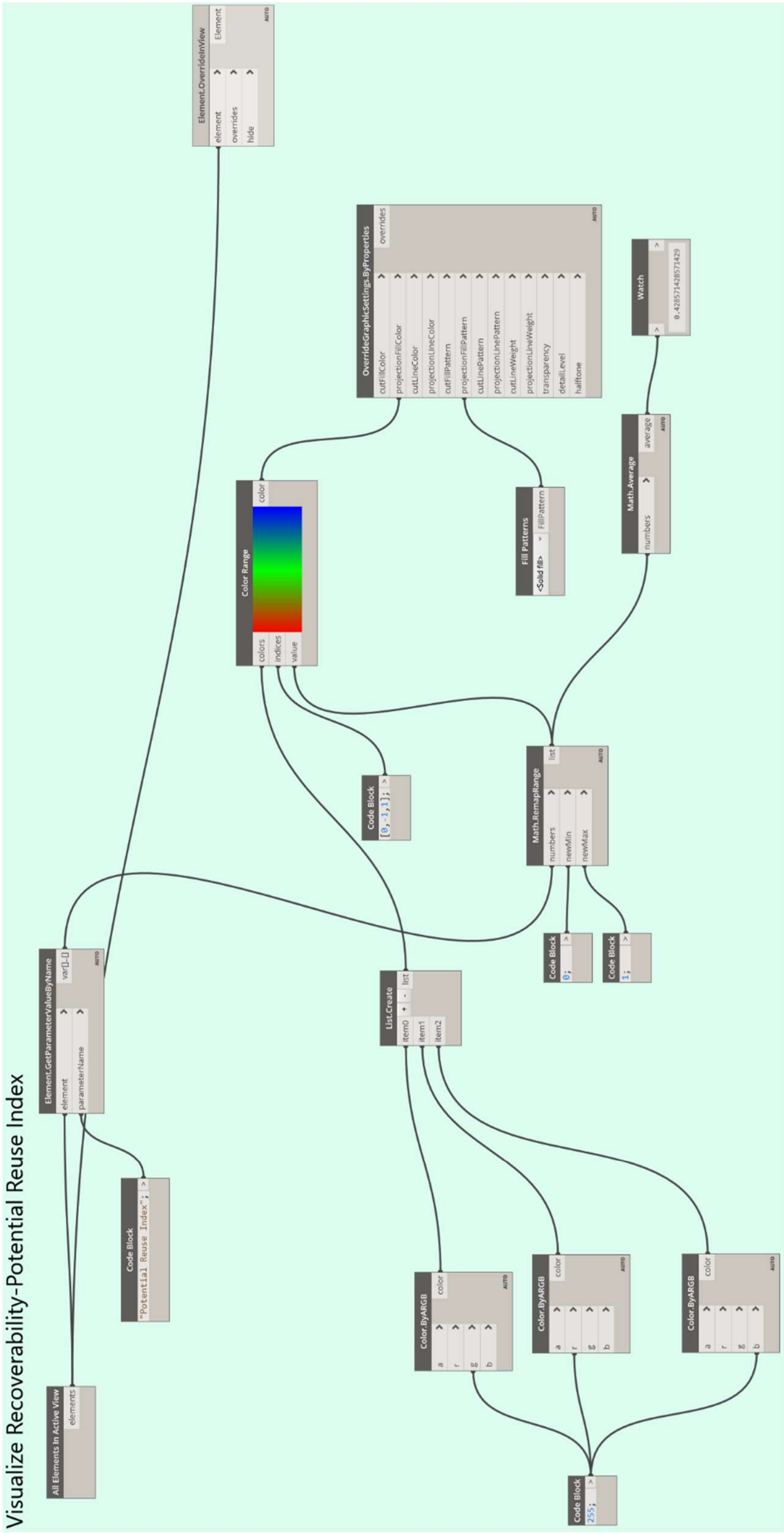
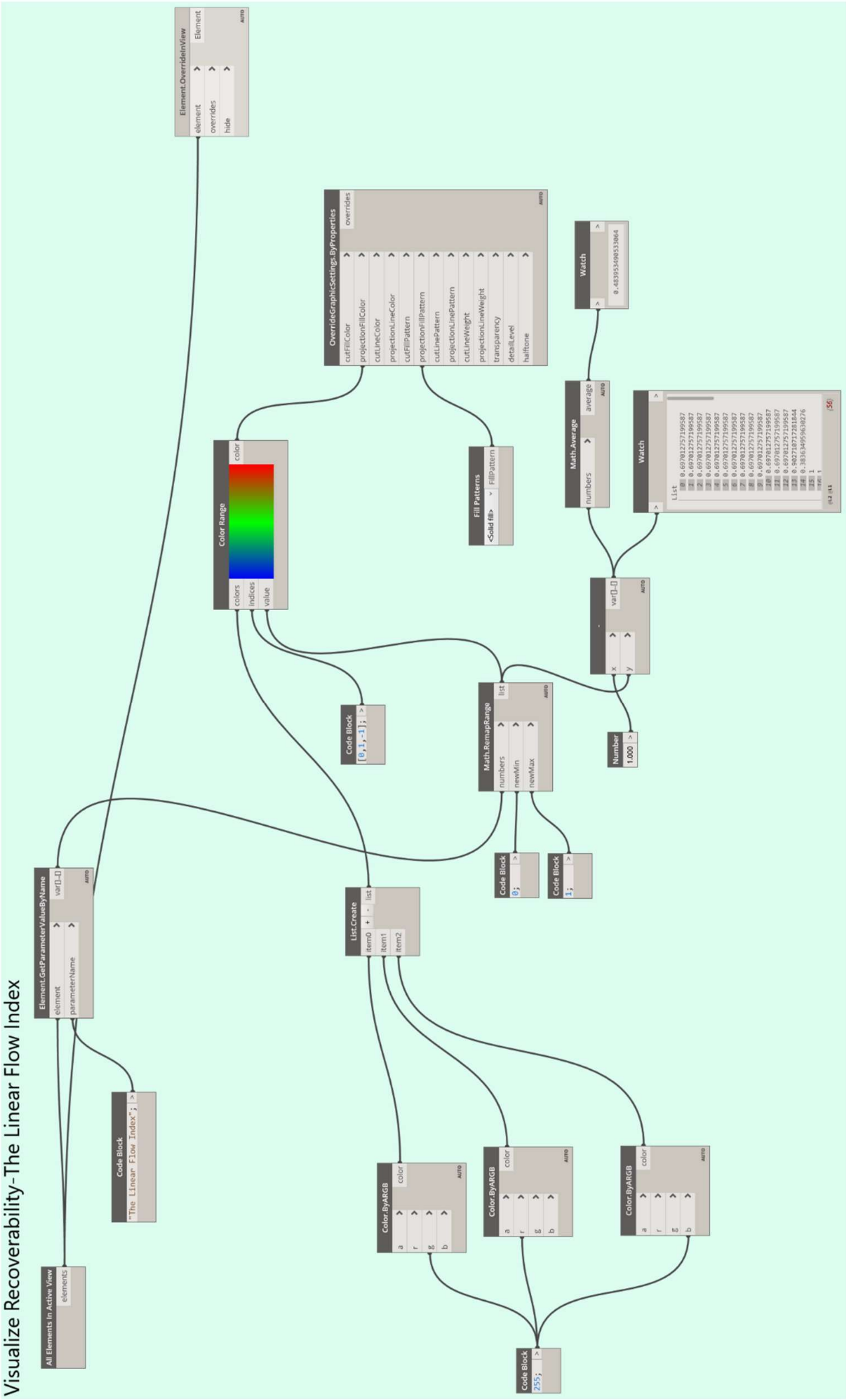
ODP
ODP-A

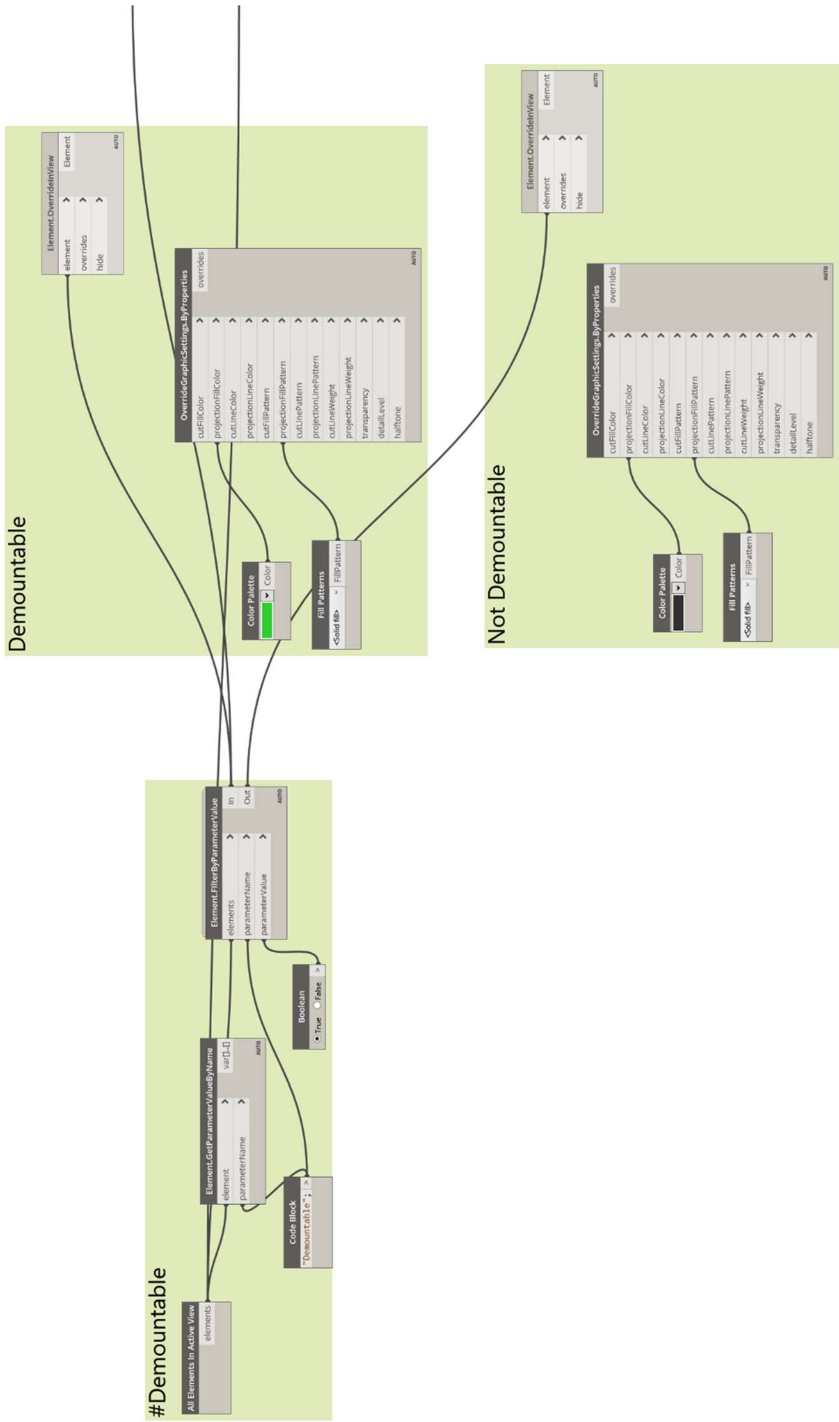

Recovery score (Atta et al., 2021)
All Elements In Active View
elements
Code Block
"Potential Recycle Index";
"Potential Reuse Index";
"The Linear Flow Index";
Element.GetParameterValueByName
element
parameterName
var[]..[]
Math.Average
numbers
average
Number
1.000
-
x
y
List Create
item0
item1
item2
list
Watch
0.280170023809524
Not Demountable
Color Palette
Color
Fill Patterns
<Solid fill>
FillPattern
OverrideGraphicSettings.ByProperties
cutFillColor
projectionFillColor
cutLineColor
projectionLineColor
cutFillPattern
projectionFillPattern
cutLinePattern
projectionLinePattern
cutLineWeight
projectionLineWeight
transparency
detailLevel
halftone
overrides
Element.OverrideInView
element
overrides
hide
Element
Deconstructability score (Atta et al., 2021)
+
/
Number
2.000
Watch
0.133928571428571

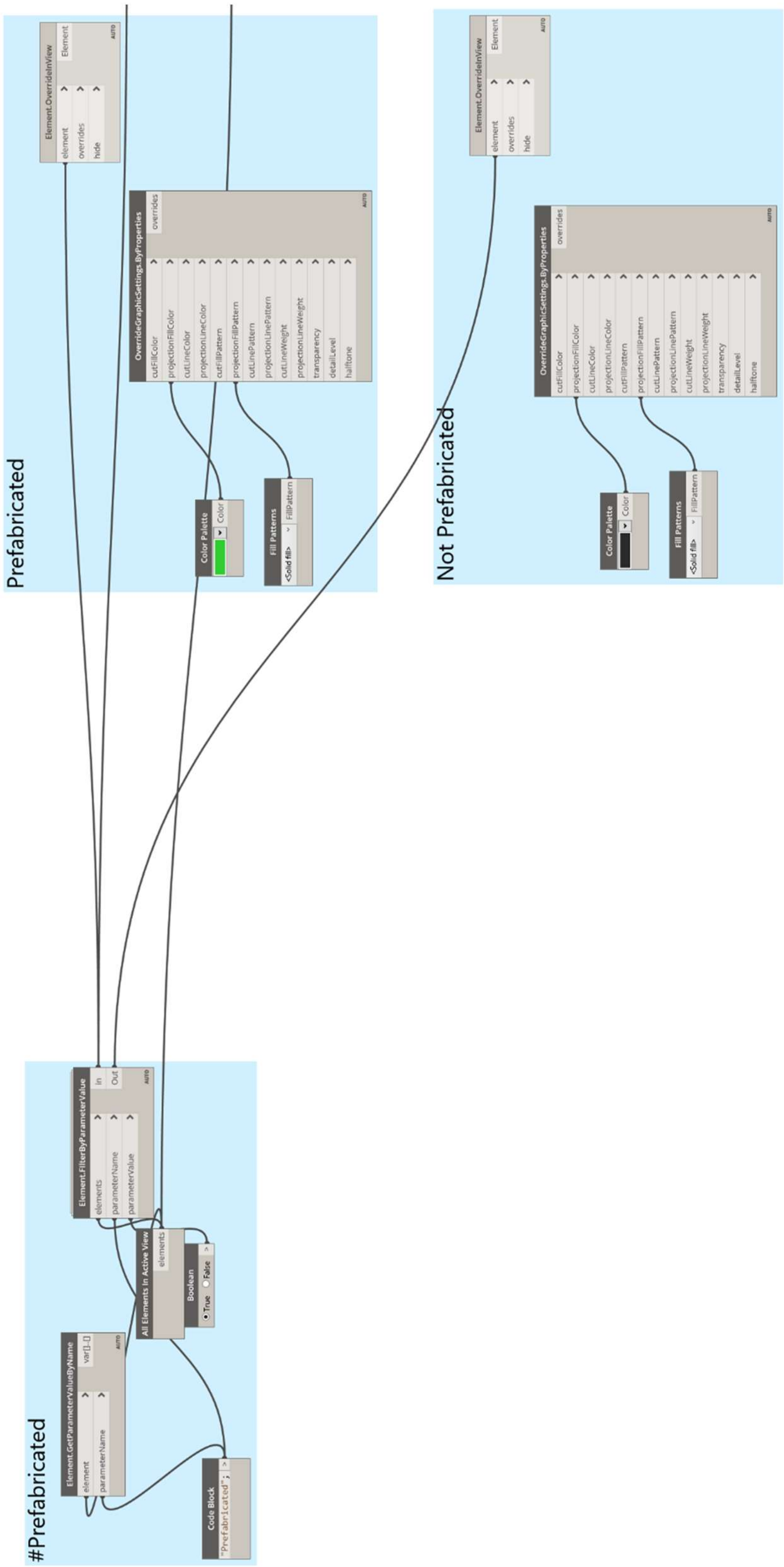

Environmental Impacts-GWP

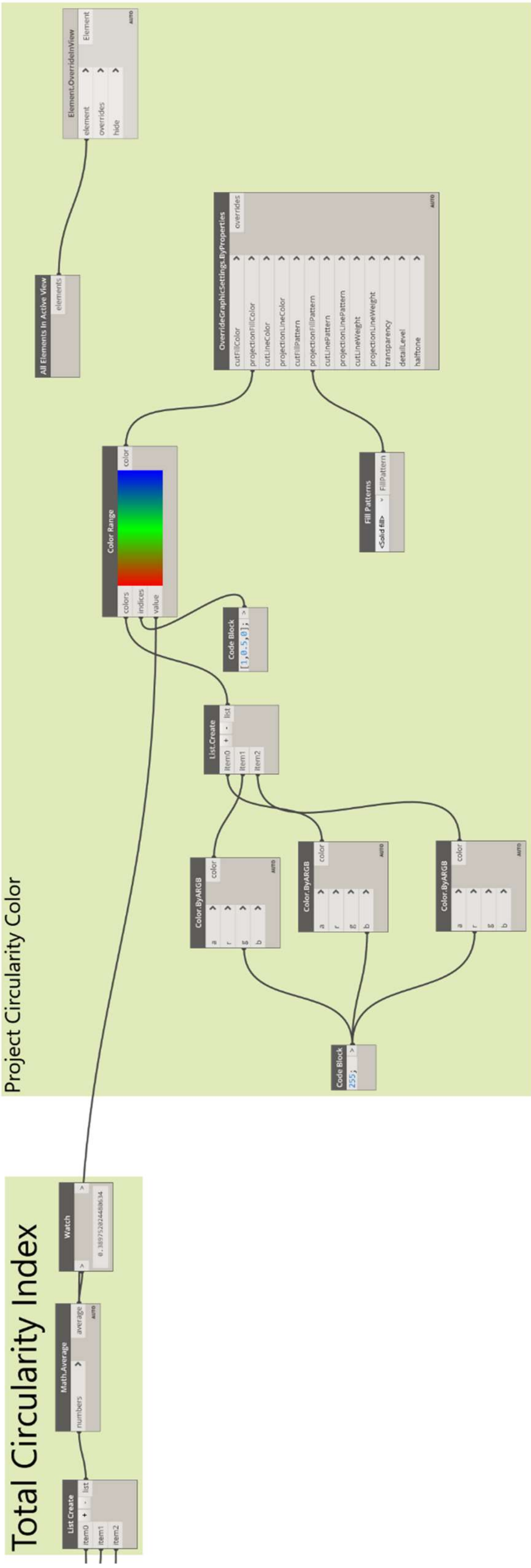

Visualize Recoverability-Potential Recycle Index
All Elements In Active View
Element.GetParameterValueByName
Code Block
"Potential Recycle Index";
Element.OverrideInView
OverrideGraphicSettings.ByProperties
Color Range
Fill Patterns
Math.Average
Watch
Math.RemapRange
List.Create
Color.ByARGB
Code Block
255;


Visualize Recoverability-Potential Reuse Index
All Elements In Active View
elements
Element.GetParameterValueByName
element
parameterName
var[]..[]
Code Block
"Potential Reuse Index";
Element.OverrideInView
element
overrides
hide
Element
OverrideGraphicSettings.ByProperties
cutFillColor
projectionFillColor
cutLineColor
projectionLineColor
cutFillPattern
projectionFillPattern
cutLinePattern
projectionLinePattern
cutLineWeight
projectionLineWeight
transparency
detailLevel
halftone
overrides
Color Range
colors
indices
value
color
Fill Patterns
<Solid fill>
FillPattern
Watch
0.428571428571429
Math.Average
numbers
average
Math.RemapRange
numbers
newMin
newMax
list
Code Block
[0,-1,1];
Code Block
0;
Code Block
1;
List.Create
item0
item1
item2
list
Color.ByARGB
a
r
g
b
color
Code Block
255;


Visualize Recoverability-The Linear Flow Index
All Elements In Active View
Element.GetParameterValueByName
Code Block
"The Linear Flow Index";
Element.OverrideInView
OverrideGraphicSettings.ByProperties
Color Range
Fill Patterns
Math.RemapRange
List.Create
Color.ByARGB
Math.Average
Watch
Number
Code Block
255;


Demountable
Element.OverrideInView
element
overrides
hide
Element
OverrideGraphicSettings.ByProperties
cutFillColor
projectionFillColor
cutLineColor
projectionLineColor
cutFillPattern
projectionFillPattern
cutLinePattern
projectionLinePattern
cutLineWeight
projectionLineWeight
transparency
detailLevel
halftone
overrides
Color Palette
Color
Fill Patterns
<Solid fill>
FillPattern
Not Demountable
#Demountable
All Elements In Active View
elements
Element.GetParameterValueByName
element
parameterName
Code Block
"Demountable";
Element.FilterByParameterValue
elements
parameterName
parameterValue
in
out
Boolean
True
False


Prefabricated
Not Prefabricated
#Prefabricated
Element.OverrideInView
OverrideGraphicSettings.ByProperties
Color Palette
Fill Patterns
Element.FilterByParameterValue
All Elements In Active View
Boolean
Element.GetParameterValueByName
Code Block
"Prefabricated";


Project Circularity Color
Total Circularity Index
List Create
Math.Average
Watch
Code Block
Color.ByARGB
Color Range
Fill Patterns
OverrideGraphicSettings.ByProperties
All Elements In Active View
Element.OverrideInView

B. List of Reference EPDs

Name	Unit	Unit Conversion	Useful Life	Climate Change (A)	Climate Change (B)	Climate Change (C)	Climate Change (D)
Adaptable Meeting Rooms Double glazed 3m x 3m	Volume	0.046296296	876000	3913.7	0	401.179	-7.65E+02
Partition Wall-glazed	Area	1	350400	5.65E+01	0	0	0.00E+00
Partition Wall-blind	Area	1	350400	3.10E+01	0	0	0.00E+00
Adaptable Wall (AW)	Area	1	876000	46.239	0	17.4486	-9.48E+00
Adaptable Meeting Rooms Single glazed 3m x 6m	Volume	0.023148148	876000	5756.9	0	360.31	-1.16E+03
Adaptable Walls			**665760**	**1960.8678**	**0**	**155.78752**	**-386.896**
Bituminous Membranes made of Recycled Polyester	Area	1	175200	0.458	0	0	0.00E+00
Non-reinforced EPDM membranes for waterproofing	Area	1	262800	2.414	0	5.33E-01	0.00E+00
multi-layer panel made of a high density bitumen based membrane and a porous textile layer	Area	1	438000	14.925	0	0.0869	0.00E+00
two layer product made of a self-adhesive high density bitumen membrane thermally bonded to a cross-linked polyethylene	Area	1	438000	0.19013	0	0.0029	0.00E+00
Bituminous Membrane			**328500**	**4.4967825**	**0**	**0.1557**	**0**
Curtain walls and punched windows	Area	0.153846154	219000	1.42E+03	0	30	-1.04E+00
Curtain wall systems	Area	1	262800	186.6	5.71E-01	13.992	-2.81E+01
Insulating glass units (IGU)-STRUGAL	Area	1	262800	86.5	0	2.5932	-15.3
Insulating glass units (IGU)	Area	1	262800	31.63	0	27.36	2.30E-01
Low-e double Glazing	Area	1	262800	33.1	9.50E-02	0.337	0.00E+00
M60 Curtain wall aluminium system	Area	1	262800	1.40E+02	0	2.689	-4.16E+01
Curtain Walls			**255500**	**316.305**	**0.111**	**12.82853333**	**-14.30166667**
CLT (Cross Laminated Timber)-reuse	Volume	1	438000	-653.8	0	764.582	-8.14E+02
CLT (Cross Laminated Timber)-recycle	Volume	1	438000	-653.8	0	770.582	-8.21E+02
CLT (Cross Laminated Timber)-recover	Volume	1	438000	-653.8	0	797.582	-3.65E+02
Cross-Laminated Timber (CLT)-reuse	Volume	1	876000	-681	0	786	-65.9
Cross-Laminated Timber (CLT)-recycle	Volume	1	876000	-681	0	791	-23.9
Cross-Laminated Timber (CLT)-recover	Volume	1	876000	-681	0	791	-537
CLT			**657000**	**-667.4**	**0**	**783.4576667**	**-437.8**
Glued Laminated Timber (Glulam)-reuse	Volume	1	876000	-510	0	1070	0
Glued Laminated Timber (Glulam)-recycle	Volume	1	876000	-510	0	1070	0
Glued Laminated Timber (Glulam)-recover	Volume	1	876000	-510	0	1070	0
Glued Laminated Timber(L.A. COST srl)	Volume	1	876000	-4.69E+02	0	0	0
Glued laminated timber(Jures)	Volume	1	438000	-746.2	0	711.06	-7.40E+02
Glulam			**788400**	**-549.04**	**0**	**784.212**	**-148.06**
OrganoWood Construction Timber	Volume	1	262800	-712.11	0	780.915	-1.16E+02
Swedish sawn dried timber of spruce or pine	Volume	1	876000	1.38E+02	0	0	0
Softwood Timber-recycle	Volume	1	876000	-718	0	906	0
Softwood Timber-recover	Volume	1	876000	-718	0	906	0
Softwood Timber-landfilled	Volume	1	876000	-718	0	421.9	0
Structural Timber			**744600**	**-563.4968571**	**0**	**654.6406667**	**-100.2657143**

Acidification (A)	Acidification (B)	Acidification (C)	Acidification (D)	Eutrophication (A)	Eutrophication (B)	Eutrophication (C)	Eutrophication (D)	Ozone Depletion (A)	Ozone Depletion (B)	Ozone Depletion (C)	Ozone Depletion (D)
18.4336	0	0.48949	-4.36E+00	0.483559	0	0.0101877	-1.28E-01	0.00045047	0	1.18188E-05	-6.53E-05
3.40E-01	0.00E+00	0.00E+00	0.00E+00	6.32E-02	0.00E+00	0.00E+00	0.00E+00	7.34E-06	0.00E+00	0.00E+00	0.00E+00
1.32E-01	0.00E+00	0.00E+00	0.00E+00	4.18E-02	0.00E+00	0.00E+00	0.00E+00	4.69E-06	0.00E+00	0.00E+00	0.00E+00
0.31441	0	0.005764	-5.04E-02	0.00761186	0	0.0000916	-2.08E-03	6.9795E-06	0	2.23E-07	-1.12E-06
27.6864	0	0.56096	-6.39E+00	0.755158	0	0.0121388	-2.02E-01	0.00063463	0	0.000013372	-8.39E-05
9.381282	**0**	**0.2112428**	**-2.16008**	**0.270265772**	**0**	**0.00448362**	**-0.066416**	**0.000220822**	**0**	**5.08282E-06**	**-0.000030064**
0.00227	0	0	0.00E+00	0.000401	0	0	0.00E+00	4.71E-08	0	0	0.00E+00
0.01056	0	9.30E-04	0.00E+00	0.002275	0	2.74E-03	0.00E+00	0.000000569	0	5.02E-08	0.00E+00
0.071289	0	0.000551	0.00E+00	0.0074831	0	0.0000717	0.00E+00	2.50745E-05	0	1.928E-08	0.00E+00
0.00111969	0	0.00001842	0.00E+00	0.00111969	0	0.00001842	0.00E+00	4.02257E-08	0	6.43E-10	0.00E+00
0.021309673	**0**	**0.000374855**	**0**	**0.002819698**	**0**	**0.00070753**	**0**	**6.43271E-06**	**0**	**1.75308E-08**	**0**
1.20E+01	0.00E+00	0	-3.79E-03	3.78E-01	0.00E+00	0.001	-8.37E-05	7.80E-05	0.00E+00	7.00E-07	-6.58E-08
1.38671	2.37E-03	0.05705	-2.26E-01	0.067157	6.48E-05	0.0005298	-1.13E-02	0.000021036	2.79E-08	1.2251E-06	-2.75E-06
0.744	0	0.009414	-0.203	1.35	0	0.02462	-0.355	5.90E-04	0	6.0889E-07	-2.65E-06
31.96	0	0.292109	1.38E-03	2.25	0	0.0233719	1.90E-04	9.78E-09	0	9.66259E-09	5.28E-14
0.16213	4.99E-04	0.002443	0.00E+00	0.00008013	3.23E-05	0.000000687	0.00E+00	2.56E-07	4.39E-09	1.15604E-15	0.00E+00
8.90E-01	0.00E+00	0.0179	-2.97E-01	1.73E-01	0.00E+00	0.0004945	-4.18E-02	1.77E-05	0.00E+00	5.319E-07	-3.01E-06
7.85714	**0.000478167**	**0.063152667**	**-0.121401667**	**0.703039522**	**1.61833E-05**	**0.008336148**	**-0.06799895**	**0.000117834**	**5.38167E-09**	**5.12592E-07**	**-1.41263E-06**
0.6027	0	0.01214	-3.89E-01	0.01589	0	0.0002045	-1.03E-02	0.00002076	0	0.000000629	-7.73E-06
0.6027	0	0.07134	-4.68E-01	0.01589	0	0.0004635	-2.72E-02	0.00002076	0	0.000001909	-7.45E-06
0.6027	0	0.20214	-1.25E-01	0.01589	0	0.0080545	2.25E-03	0.00002076	0	0.000003299	-5.32E-05
1.07	0	0	-0.609	0.149	0	0	-0.137	1.31E-09	0	0	-1.64E-10
1.07	0	0.0304	-0.235	0.149	0	0.00714	-0.0498	1.31E-09	0	9.59E-16	-2.11E-11
1.07	0	0.0304	-0.0168	0.149	0	0.00714	-0.0381	1.31E-09	0	9.59E-16	-1.60E-14
0.83635	**0**	**0.057736667**	**-0.307133333**	**0.082445**	**0**	**0.00383375**	**-0.043358333**	**1.03807E-05**	**0**	**9.72833E-07**	**-1.13967E-05**
2.605	0	0.04135	0	0.5325	0	0.00969	0	2.795E-10	0	2.83E-13	0.00E+00
2.605	0	0	0	0.5325	0	0	1	2.795E-10	0	0	0.00E+00
2.605	0	0.04135	0	0.5325	0	0.00969	2	2.795E-10	0	2.83E-13	0.00E+00
6.39E-01	0	0	0	1.91E+00	0	0	0	1.98E+00	0	0	0.00E+00
0.7111	0	0.093943	-1.30E+00	0.030595	0	0.00371667	-1.56E-02	0.0000363	0	2.4193E-06	-6.14E-05
1.83302	**0**	**0.0353286**	**-0.2604**	**0.707619**	**0**	**0.004619334**	**0.596882**	**0.39600726**	**0**	**4.8386E-07**	**-0.000012274**
0.4125	0	0.2627	-3.84E-01	0.0064995	0	0.00061091	-1.87E-02	9.29E-06	0	0.000001738	-7.40E-06
2.09E-01	0	0	0	5.02E-02	0	0	0	0	0	0	0.00E+00
0.963	0	0.0352	0	0.263	0	0.00818	0	2.24E-13	0	9.87E-16	0.00E+00
0.963	0	0.0352	0	0.263	0	0.00818	0	2.24E-13	0	9.87E-16	0.00E+00
0.963	0	0.366	0	0.263	0	0.047	0	2.24E-13	0	3.98E-13	0.00E+00
0.882838571	**0**	**0.113166467**	**-0.135933333**	**0.2336805**	**0**	**0.010346285**	**0.076403381**	**0.056575276**	**0**	**4.56385E-07**	**-4.43867E-06**

mass of virgin feedstock	mass of unrecoverable waste	mass of unrecoverable waste generated when producing recycled feedstock	mass of unrecoverable waste generated in the process of recycling parts	mass of recyclable component	mass of reusable component	number of times the component is reused	total mass	The Linear Flow Index	Potential Recycle Index	Potential Reuse Index
1593	389.75	0	0	352.2	851.05	1	1593	0.622332078	0.221092279	0.534243566
85.8557	1.5165	0.00E+00	0.00E+00	22.1635	76.32	1	100	0.436861	0.221635	0.7632
63.7972	0.779	0.00E+00	0.00E+00	11.571	0	0	100	0.322881	0.11571	0
32.7	5.705	0	0	1.4	25.595	1	32.7	0.587232416	0.042813456	0.782721713
1593	389.75	0	0	352.2	851.05	1	1593	0.622332078	0.221092279	0.534243566
673.67058	**157.5001**	**0**	**0**	**147.9069**	**360.803**	**0.8**	**683.74**	**0.518327714**	**0.164468603**	**0.522881769**
100	21	0	0	0	0	0	100	0.605	0	0
6.88E+00	6.88E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7	1	0	0
100	100	0	0	0	0	0	100	1	0	0
100	100	0	0	0	0	0	100	1	0	0
76.71946766	**56.96946766**	**0**	**0**	**0**	**0**	**0**	**76.71946766**	**0.90125**	**0**	**0**
268.4	226.254	0	0	41.6958	0.4502	0	268.4	0.921486587	0.155349478	0
300	8.00E+01	0	0.00E+00	125	0.00E+00	0	300	0.633333333	0.416666667	0
300	80	0	0	125	0.00E+00	0	300	0.633333333	0.416666667	0
2.50E+00	1.75E+00	0.00E+00	0.00E+00	7.50E-01	0.00E+00	0.00E+00	2.5	0.85	0.3	0
20	20	0	0	0	0	0	20	1	0	0
1.00E+02	7.00E+01	0.00E+00	0.00E+00	3.00E+01	0.00E+00	0.00E+00	1.00E+02	0.85	0.3	0
165.15	**79.66733333**	**0**	**0**	**53.74096667**	**0.075033333**	**0**	**165.15**	**0.814692209**	**0.264780469**	**0**
100	0	0	0	0	1.00E+02	1	100	0.5	0	1
100	1	0	0	99	0.00E+00	0	100	0.505	0.99	0
100	25	0	0	0	0.00E+00	0	100	0.625	0	0
100	0	0	0	0	1.00E+02	1	100	0.5	0	1
100	1	0	0	99	0.00E+00	0	100	0.505	0.99	0
100	25	0	0	0	0.00E+00	0	100	0.625	0	0
100	**8.666666667**	**0**	**0**	**33**	**33.33333333**	**0.333333333**	**100**	**0.543333333**	**0.33**	**0.333333333**
100	0	0	0	0	100	1	100	0.5	0	1
100	0	0	0	100	0.00E+00	0	100	0.5	1	0
100	0	0	0	0	0.00E+00	0	100	0.5	0	0
1.22E+02	1.22E+02	0	0	2.18E-02	0.00E+00	0	122.0571	0.999821395	0.000178605	0
476	0	0	0	0	0.00E+00	0	476	0.5	0	0
179.60706	**24.40706**	**0**	**0**	**20.00436**	**20**	**0.2**	**179.61142**	**0.599964279**	**0.200035721**	**0.2**
2.32E+00	3.42E-01	0	0	2.97E+00	0.00E+00	0	5.2918	0.251672399	0.561245701	0
2.32E+00	3.42E-01	0	0	2.97E+00	0.00E+00	0	5.2918	0.251672399	0.561245701	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	100	0.5	1	0
1.00E+02	0.00E+00	0	0	0.00E+00	0.00E+00	0	100	0.5	0	0
100	100	0	0	0	0	0	100	1	0	0
83.46438	**19.10818952**	**0**	**0**	**22.70633714**	**7.619047619**	**0.076190476**	**84.31357429**	**0.520948916**	**0.378932446**	**0.076190476**

Ready Mix Concrete	Volume	1	438000	228.447	-1.43E+01	34.327	-4.56E-01
1 m3 of Ready-Mix Concrete	Volume	1	876000	100.43	0	50.6	0
Ready Mixed Concrete C20/25	Volume	1	438000	223.64	-1.15E+01	14.24	-9.03E+00
Ready-Mix Concrete(BGC)	Volume	1	876000	288	0	36.14	-5.20E+00
Ready Mix Concrete			**657000**	**210.12925**	**-6.45**	**33.82675**	**-3.6715**
Precast solid concrete walls and floors	Volume	2.41	876000	1.74E+02	0	0	0.00E+00
Solid precast concrete floor slab	Volume	2.41	438000	208.6	0	12.87	-5.64E+00
Precast concrete floor slab			**657000**	**191.3**	**0**	**6.435**	**-2.822**
Precast concrete beams	Volume	2.41	438000	2.06E+02	0.00E+00	13.31	-5.50E+00
Precast Concrete Column And Beam	Volume	2.41	876000	1.50E+02	0	6.06E+00	-2.54E+01
Precast concrete columns	Volume	2.41	438000	2.24E+02	0	1.74E+01	4.35E+00
Precast concrete columns and beams			**584000**	**1.93E+02**	**0**	**1.23E+01**	**-8.848333333**
Insulated precast concrete sandwich walls (Sollebrunns)	Volume	2.41	876000	3.15E+02	0	0.00E+00	0.00E+00
Insulated precast concrete walls (K-Prefab AB)	Volume	2.41	876000	1.48E+02	0	8.93E+00	-1.20E+01
Insulated precast concrete. sandwich wall	Volume	2.41	438000	2.22E+02	-2.10E+00	0.00E+00	0.00E+00
Precast solid concrete walls and floors	Volume	2.41	876000	1.74E+02	0	0	0.00E+00
Sandwich Wall	Volume	2.41	876000	1.64E+02	0.00E+00	1.63E+01	-9.84E+00
Solid precast concrete insulated lightweight wall	Volume	2.41	876000	5.16E+02	0	0.00E+00	0.00E+00
Solid precast concrete insulated wall (Half Sandwich)	Volume	2.41	876000	2.61E+02	0.00E+00	0.00E+00	0.00E+00
Recycleable Precast solid concrete walls ECO 30	Volume	2.41	876000	1.22E+02	0	0.00E+00	0.00E+00
Insulated precast concrete sandwich walls			**821250**	**2.40E+02**	**-2.63E-01**	**3.16E+00**	**-2.73E+00**
Parquet from hardwood. biogenic CO2 not substracted	Area	1	350400	-5.274	0	1.46E+01	-6.13E+00
Recycled Raised Floor Panels	Area	2.777777778	219000	4.29E-01	0	8.23E-01	0.00E+00
Multilayer wood flooring	Area	1	219000	4.62	0	1.29E+01	4.89E-01
White marble tiles	Volume	0.384615385	438000	8.39E+02	1.23E+01	1.34E+01	0.00E+00
Vinyl Floor Covering	Area	1	876000	8.57E+02	3.16E+01	6.60E+02	-1.63E+02
Flocked Floor Covering (vinyl)	Area	1	876000	8.21E+02	3.16E+01	3.15E+02	-1.34E+02
Vinyl Floor Covering	Area	1	876000	7.13E+02	3.31E+01	7.70E+02	-1.97E+02
Different Types of Flooring			**550628.5714**	**4.61E+02**	**1.55E+01**	**2.55E+02**	**-7.14E+01**

0.6788	0	0.3199	-3.14E-02	0.091234	0	0.01772	4.62E-03	0.00001416	-1.43E+01	0.000009953	-2.01E-07
0.4224	0	0.34608	0	0.000039162	0	0.000064013	0	9.1099E-11	0	8.5067E-11	0.00E+00
0.54223	0	0.2225	-6.38E-02	0.040079	0	0.01327	-1.16E-02	0.000007799	0	0.000005488	-6.14E-07
0.99	0	0.30032	-4.63E-02	9.37E-03	0	0.000009351	-8.45E-06	6.61E-06	0	0.000005474	-5.52E-07
0.6583575	**0**	**0.2972**	**-0.035375**	**0.035180541**	**0**	**0.007765841**	**-0.001747113**	**7.14227E-06**	**-3.575**	**5.22877E-06**	**-3.4175E-07**
6.29E-01	0.00E+00	0.00E+00	0.00E+00	6.60E-02	0.00E+00	0.00E+00	0.00E+00	7.14E-08	0.00E+00	0.00E+00	0.00E+00
0.806	0	0.10641	-3.64E-02	0.005544	0	0.00013682	-3.58E-04	0.000013526	0	3.1156E-06	-5.05E-07
0.7175	**0**	**0.053205**	**-0.0182**	**0.035772**	**0**	**0.00006841**	**-0.000179**	**6.7987E-06**	**0**	**1.5578E-06**	**-2.525E-07**
0.95502	0.00E+00	112.23	-3.55E-02	0.0055811	0.00E+00	0.17499	-3.48E-04	1.46173E-05	0.00E+00	3.1699E-06	-4.92E-07
4.73E-01	0.00E+00	4.89E-02	-9.05E-02	9.58E-03	0.00E+00	2.54E-04	1.43E-02	8.42E-06	0.00E+00	1.36E-06	6.15E-07
8.70E-01	0.00E+00	1.06E-01	2.65E-02	**7.04E+00**	0.00E+00	8.34E-01	2.08E-01	**4.27E-04**	0.00E+00	1.65E-03	4.13E-04
7.66E-01	**0.00E+00**	**3.75E+01**	**-3.32E-02**	**2.35E+00**	**0.00E+00**	**3.36E-01**	**7.41E-02**	**1.50E-04**	**0**	**5.53E-04**	**0.000137808**
1.10E+00	0.00E+00	0.00E+00	0.00E+00	4.90E-01	0.00E+00	0.00E+00	0.00E+00	1.35E-05	0.00E+00	0.00E+00	0.00E+00
7.58E-01	0.00E+00	4.73E-02	-7.51E-02	9.59E-03	0.00E+00	2.44E-04	4.16E-03	8.12E-06	0.00E+00	1.30E-06	-4.02E-07
5.32E-01	0.00E+00	0.00E+00	0.00E+00	2.65E-01	0.00E+00	0.00E+00	0.00E+00	9.08E-06	0.00E+00	0.00E+00	0.00E+00
6.29E-01	0.00E+00	0.00E+00	0.00E+00	6.60E-02	0.00E+00	0.00E+00	0.00E+00	7.14E-08	0.00E+00	0.00E+00	0.00E+00
6.75E-01	0.00E+00	1.18E-01	-5.47E-02	3.27E-03	0.00E+00	1.47E-04	-5.45E-04	8.47E-06	0.00E+00	3.81E-06	-6.65E-07
1.83E+00	0.00E+00	0.00E+00	0.00E+00	6.71E-01	0.00E+00	0.00E+00	0.00E+00	3.79E-05	0.00E+00	0.00E+00	0.00E+00
7.39E-01	0.00E+00	0.00E+00	0.00E+00	2.41E-01	0.00E+00	0.00E+00	0.00E+00	1.84E-05	0.00E+00	0.00E+00	0.00E+00
2.36E-01	0.00E+00	0.00E+00	0.00E+00	6.50E-02	0.00E+00	0.00E+00	0.00E+00	3.09E-06	0.00E+00	0.00E+00	0.00E+00
8.13E-01	**0.00E+00**	**2.06E-02**	**-1.62E-02**	**2.26E-01**	**0.00E+00**	**4.89E-05**	**4.52E-04**	**1.23E-05**	**0.00E+00**	**6.38E-07**	**-1.33E-07**
4.44E-02	0.00E+00	1.17E-04	-6.48E-03	9.84E-03	0.00E+00	1.76E-05	-6.73E-05	1.54E-06	0.00E+00	1.57E-08	-1.44E-06
2.08E-03	0.00E+00	9.50E-04	0.00E+00	2.31E-04	0.00E+00	9.61E-05	0.00E+00	1.88E-07	0.00E+00	5.23E-08	0.00E+00
3.54E-02	0.00E+00	1.98E-03	-1.38E-01	1.72E-04	0.00E+00	6.31E-07	-2.98E-03	8.11E-07	0.00E+00	3.36E-08	-8.84E-09
4.33E+00	4.86E-02	7.22E-02	0.00E+00	2.90E-01	1.08E-01	3.21E-03	0.00E+00	1.41E-04	6.25E-07	4.01E-06	0.00E+00
2.08E+00	7.82E-02	8.83E-01	-2.74E-01	3.05E-01	1.07E-02	3.15E-02	-2.97E-02	6.85E-06	2.06E-07	6.09E-11	-3.55E-10
1.54E+00	7.82E-02	1.84E-01	-2.26E-01	2.43E-01	1.07E-02	4.20E-02	-2.44E-02	4.54E-06	2.06E-07	8.88E-12	-2.93E-10
1.87E+00	8.32E-02	1.03E+00	-3.17E-01	2.09E-01	1.10E-02	3.66E-02	-3.31E-02	5.84E-06	2.07E-07	3.51E-10	-3.92E-09
1.41E+00	**4.12E-02**	**3.10E-01**	**-1.37E-01**	**1.51E-01**	**2.01E-02**	**1.62E-02**	**-1.29E-02**	**2.30E-05**	**1.78E-07**	**5.87E-07**	**-2.08E-07**

1.00E+02	3.90E+01	0.00E+00	0.00E+00	6.10E+01	0.00E+00	0.00E+00	1.00E+02	0.695	0.61	0
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
1.00E+02	5.00E+01	0.00E+00	0.00E+00	5.00E+01	0.00E+00	0.00E+00	1.00E+02	0.75	0.5	0
559	559	0.00E+00	0.00E+00	1.77E+03	0.00E+00	0.00E+00	2330	0.239914163	0.760085837	0
214.75	**187**	**0**	**0**	**470.5**	**0**	**0**	**657.5**	**0.671228541**	**0.467521459**	**0**
1.00E+02	9.90E+01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	1.00E+02	0.995	0.01	0
2.00E+02	4.00E+01	0.00E+00	0.00E+00	1.60E+02	0.00E+00	0.00E+00	2.00E+02	0.6	0.8	0
150	**69.5**	**0**	**0**	**80.5**	**0**	**0**	**150**	**0.7975**	**0.405**	**0**
2.00E+02	4.00E+01	0.00E+00	0.00E+00	1.60E+02	0.00E+00	0.00E+00	2.00E+02	0.6	0.8	0
5.00E+01	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	1.00E+02	0.25	1	0
2.00E+02	4.00E+01	0.00E+00	0.00E+00	1.60E+02	0.00E+00	0.00E+00	2.00E+02	0.6	0.8	0
150	**26.66666667**	**0**	**0**	**140**	**0**	**0**	**166.6666667**	**0.483333333**	**0.866666667**	**0**
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
3.00E+02	0.00E+00	0.00E+00	0.00E+00	2.00E+02	0.00E+00	0.00E+00	3.00E+02	0.5	0.666666667	0
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
1.00E+02	9.90E+01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	1.00E+02	0.995	0.01	0
2.00E+02	2.50E+01	0.00E+00	0.00E+00	1.75E+02	0.00E+00	0.00E+00	2.00E+02	0.5625	0.875	0
1.00E+02	9.90E+01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	1.00E+02	0.995	0.01	0
1.00E+02	9.90E+01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	1.00E+02	0.995	0.01	0
9.78E+01	3.25E+01	0.00E+00	0.00E+00	6.53E+01	0.00E+00	0.00E+00	9.78E+01	0.666024629	0.667950741	0
137.2202125	**69.3077125**	**0**	**0**	**55.4125**	**0**	**0**	**1.37E+02**	**0.839190579**	**0.279952176**	**0**
3.80E+01	6.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.22	0	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	9.00E+01	1.00E+01	1.00E+00	1.00E+02	0.5	0.9	0.1
1.00E+02	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	1.00E+02	0.5	1	0
1.00E+03	1.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+03	1	0	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.5	0	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.5	0	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.5	0	0
219.7142857	**143.7142857**	**0**	**0**	**27.14285714**	**1.428571429**	**0.142857143**	**228.5714286**	**0.531428571**	**0.271428571**	**0.014285714**

Extensive Green Roof System: Veg Tech Sedumtak 0-2	Area	1	350400	1.14E+01	1.12E-02	1.30E+01	-2.02E+00
Extensive Green Roof System: Veg Tech Sedumtak 1-27 (without or with extra drainage)	Area	1	350400	1.11E+01	1.12E-02	1.07E+01	-1.60E+00
Urbanscape® Green Roof System	Area	1	438000	6.31E+00	-6.11E+01	6.83E+01	-1.11E+00
Green Roof			**379600**	**9.58E+00**	**-2.04E+01**	**3.07E+01**	**-1.58E+00**
Earthwool	Area	1	438000	3.25E+00	0.00E+00	3.64E-01	-3.25E-02
Knauf Insulation German Plants	Area	1	438000	3.24E+00	0.00E+00	4.06E-01	-7.04E-02
Glass Mineral Wool	Area	1	438000	1.50E+00	0.00E+00	2.20E-02	-8.42E-02
Earthwool			**438000**	**2.66E+00**	**0**	**2.64E-01**	**-0.062366667**
Reusable Roof Insulation Boards	Area	1	350400	2.28E+00	2.13E+00	9.49E-02	0.00E+00
Rigid Roof Insulation	Area	1	438000	1.51E+01	0.00E+00	2.22E-01	-2.97E-01
Rigid Roof Insulation	Area	1	438000	1.78E+02	0.00E+00	2.63E+00	-5.94E-01
Rigid Roof Insulation			**438000**	**9.67E+01**	**0**	**1.43E+00**	**-0.4455**
Straw as insulation material	Volume	1	657000	-1.16E+02	0.00E+00	1.31E+02	-6.49E+00
Metal Deck	Area	1	438000	2.32E+01	0.00E+00	1.44E-01	-7.13E+00
Metal Deck	Volume	0.000408163	350400	1.88E+00	0.00E+00	0.00E+00	0.00E+00
Trapezoidal Corrugated Steel Sheet	Area	1	438000	2.32E+01	0.00E+00	1.44E-01	-7.13E+00
Metal Deck			**408800**	**1.61E+01**	**0.00E+00**	**9.60E-02**	**-4.75E+00**
Insulated metal sandwich panels for walls. ceilings and roofings	Area	1	438000	4.07E+01	0.00E+00	0.00E+00	0.00E+00
Insulated metal sandwich panels for walls. ceilings and roofings	Area	1	438000	3.45E+01	0.00E+00	0.00E+00	0.00E+00
Insulated metal sandwich panels for walls. ceilings and roofings			**438000**	**3.76E+01**	**0**	**0**	**0**
Plywood from pine	Volume	1	350400	-5.20E+02	0.00E+00	7.94E+02	-8.55E+01
Multilayer panels of poplar plywood	Volume	1	350400	4.99E+02	0.00E+00	9.56E+00	-1.28E+01
Spruce plywood	Volume	1	876000	-6.67E+02	0.00E+00	8.63E+02	-2.98E+02
Poplar plywood	Volume	1	350400	2.14E+02	0.00E+00	0.00E+00	0.00E+00
Raw birch plywood	Volume	1	350400	8.26E+02	0.00E+00	0.00E+00	0.00E+00
Plywood	Volume	1	350400	-3.37E+02	0.00E+00	5.11E+02	-3.21E+01
Plywood			**438000**	**2.47E+00**	**0**	**3.63E+02**	**-71.4**
C24 Graded. treated kiln-dried and planed carcassing	Volume	1	525600	-6.29E+02	0.00E+00	7.49E+02	-7.62E+02
Prefabricated Timber Frame Wall System-recycle	Volume	0.006	438000	-1.02E+00	0.00E+00	1.63E+00	-6.22E-01
Prefabricated Timber Frame Wall System-reuse	Volume	0.006	438000	-1.02E+00	0.00E+00	1.59E+00	-1.80E+00
Construction panel	Area	1	438000	1.07E-01	0.00E+00	1.57E-01	-1.30E-02
Prefabricated Timber Frame Wall System			**459900**	**-1.58E+02**	**0.00E+00**	**1.88E+02**	**-1.91E+02**

2.29E-02	2.72E-05	3.32E-03	-2.52E-03	3.28E-04	8.66E-07	2.58E-05	-4.45E-05	5.95E-07	3.16E-17	1.52E-15	-1.62E-09
1.07E-01	2.72E-05	5.10E-03	-1.33E-03	3.17E-03	8.66E-07	2.59E-05	-2.43E-05	6.93E-07	3.16E-17	1.63E-15	-1.62E-09
2.91E-02	1.48E-02	4.70E-03	-1.40E-03	2.01E-04	2.05E-07	-8.70E-06	-1.37E-06	4.20E-14	1.22E-15	2.44E-15	-1.20E-14
5.30E-02	**4.95E-03**	**4.38E-03**	**-1.75E-03**	**1.23E-03**	**6.45667E-07**	**1.43E-05**	**-0.00002339**	**4.29E-07**	**4.28E-16**	**1.87E-15**	**-1.08E-09**
1.85E-02	0.00E+00	2.77E-04	-1.94E-04	9.41E-05	0.00E+00	2.44E-06	-1.43E-06	2.31E-13	0.00E+00	2.07E-14	-8.63E-14
1.75E-02	0.00E+00	2.66E-04	-2.23E-04	1.07E-04	0.00E+00	2.35E-06	-1.41E-06	7.53E-14	0.00E+00	1.99E-14	-7.24E-14
1.03E-02	0.00E+00	7.50E-04	-9.71E-05	2.24E-03	0.00E+00	1.81E-04	-1.29E-05	4.82E-11	0.00E+00	1.88E-14	-1.03E-15
1.54E-02	**0**	**4.31E-04**	**-0.000171367**	**8.13E-04**	**0**	**6.19E-05**	**-5.24667E-06**	**1.62E-11**	**0.00E+00**	**1.98E-14**	**-5.32E-14**
1.12E-02	1.02E-02	1.28E-04	0.00E+00	3.92E-03	1.54E-02	1.31E-02	0.00E+00	1.73E-07	1.58E-07	2.57E-09	0.00E+00
1.36E-01	0.00E+00	1.34E-03	-3.96E-04	3.81E-03	0.00E+00	1.76E-04	-5.76E-05	1.08E-10	0.00E+00	9.85E-16	-3.80E-13
1.76E+00	0.00E+00	1.60E-02	-8.01E-04	8.27E-02	0.00E+00	2.51E-03	-8.50E-05	4.13E-09	0.00E+00	2.60E-11	-1.51E-10
9.48E-01	**0**	**8.64E-03**	**-0.0005985**	**4.33E-02**	**0**	**1.34E-03**	**-0.0000713**	**2.12E-09**	**0**	**1.30E-11**	**-7.569E-11**
1.43E-01	0.00E+00	4.21E-02	-1.89E-01	4.69E-03	0.00E+00	6.40E-05	-5.97E-04	1.05E-06	0.00E+00	5.64E-07	-1.70E-06
9.79E-02	0.00E+00	1.27E-03	-3.20E-02	6.72E-03	0.00E+00	5.87E-06	-3.33E-03	1.06E-06	0.00E+00	3.26E-08	-3.40E-07
1.33E-02	0.00E+00	0.00E+00	0.00E+00	3.57E-03	0.00E+00	0.00E+00	0.00E+00	1.74E-07	0.00E+00	0.00E+00	0.00E+00
9.79E-02	0.00E+00	1.27E-03	-3.20E-02	6.72E-03	0.00E+00	5.87E-06	-3.33E-03	1.06E-06	0.00E+00	3.26E-08	-3.40E-07
6.97E-02	**0.00E+00**	**8.47E-04**	**-2.13E-02**	**5.67E-03**	**0.00E+00**	**3.91E-06**	**-2.22E-03**	**7.63E-07**	**0.00E+00**	**2.17E-08**	**-2.27E-07**
2.25E-01	0.00E+00	0.00E+00	0.00E+00	3.65E+00	0.00E+00	0.00E+00	0.00E+00	2.39E-06	0.00E+00	0.00E+00	0.00E+00
1.92E-01	0.00E+00	0.00E+00	0.00E+00	8.97E-02	0.00E+00	0.00E+00	0.00E+00	1.65E-06	0.00E+00	0.00E+00	0.00E+00
2.08E-01	**0**	**0**	**0**	**1.87E+00**	**0**	**0**	**0**	**2.02E-06**	**0**	**0**	**0**
3.13E+00	0.00E+00	4.23E-01	-5.04E-01	5.62E-04	0.00E+00	4.84E-05	-4.34E-03	3.53E-13	0.00E+00	5.09E-14	-3.74E-13
3.26E+00	0.00E+00	2.35E-01	-4.68E-02	1.05E+00	0.00E+00	5.90E-02	-1.34E-02	7.41E-05	0.00E+00	1.13E-06	-1.49E-06
1.51E+00	0.00E+00	1.25E-01	-3.88E-01	4.49E-03	0.00E+00	2.67E-05	-3.89E-04	7.10E-06	0.00E+00	1.09E-13	-3.40E-12
1.17E+00	0.00E+00	0.00E+00	0.00E+00	4.70E-01	0.00E+00	0.00E+00	0.00E+00	3.12E-05	0.00E+00	0.00E+00	0.00E+00
4.58E-01	0.00E+00	0.00E+00	0.00E+00	4.27E+00	0.00E+00	0.00E+00	0.00E+00	8.33E-05	0.00E+00	0.00E+00	0.00E+00
6.22E+00	0.00E+00	2.68E-01	-1.06E-01	3.23E+00	0.00E+00	3.06E-03	-3.54E-03	4.66E-05	0.00E+00	8.31E-06	-6.32E-06
2.62E+00	**0**	**1.75E-01**	**-0.174133333**	**1.50E+00**	**0**	**1.04E-02**	**-0.0036115**	**4.04E-05**	**0**	**1.57E-06**	**-1.30167E-06**
9.12E-01	0.00E+00	2.58E-02	-7.97E-01	8.77E-02	0.00E+00	1.39E-03	-4.72E-02	1.59E-05	0.00E+00	1.16E-06	-1.05E-04
2.27E-03	0.00E+00	2.50E-04	-3.80E-03	3.52E-04	0.00E+00	3.96E-05	-4.81E-04	2.27E-07	0.00E+00	2.86E-09	-3.08E-08
2.27E-03	0.00E+00	7.21E-05	-1.37E-03	3.52E-04	0.00E+00	2.83E-06	-1.78E-04	2.27E-07	0.00E+00	3.39E-09	-1.67E-08
3.20E-02	0.00E+00	1.14E-03	-5.50E-04	3.27E-03	0.00E+00	3.52E-05	-1.20E-04	6.00E-07	0.00E+00	4.54E-08	-4.90E-09
2.37E-01	**0.00E+00**	**6.80E-03**	**-2.01E-01**	**2.29E-02**	**0.00E+00**	**3.66E-04**	**-1.20E-02**	**4.24E-06**	**0.00E+00**	**3.04E-07**	**-2.63E-05**

32	0.00E+00	0.00E+00	0.00E+00	30.4	0.00E+00	0.00E+00	32	0.5	0.95	0
32	0.00E+00	0.00E+00	0.00E+00	30.4	0.00E+00	0.00E+00	32	0.5	0.95	0
2.00E+02	0.00E+00	0.00E+00	0.00E+00	20	1.00E+02	1.00E+00	200	0.5	0.1	0.5
88	**0**	**0**	**0**	**26.93333333**	**33.33333333**	**0.333333333**	**88**	**0.5**	**0.666666667**	**0.166666667**
1.00E+02	0.00E+00	0.00E+00	0.00E+00	7.00E+01	0.00E+00	0.00E+00	1.00E+02	0.5	0.7	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	7.00E+01	0.00E+00	0.00E+00	1.00E+02	0.5	0.7	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	7.30E+01	0.00E+00	0.00E+00	1.00E+02	0.5	0.73	0
100	**0**	**0**	**0**	**71**	**0**	**0**	**100**	**0.5**	**0.71**	**0**
2.00E+02	1.00E+01	0.00E+00	0.00E+00	0.00E+00	1.90E+02	1.00E+00	2.00E+02	0.525	0	0.95
7.20E+01	72	0.00E+00	0.00E+00	2.80E+01	0.00E+00	0.00E+00	1.00E+02	0.72	0.28	0
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
86	**86**	**0**	**0**	**14**	**0**	**0**	**100**	**0.86**	**0.14**	**0**
3.33E+01	33.3	0.00E+00	0.00E+00	3.34E+01	0.00E+00	0.00E+00	1.00E+02	0.333	0.334	0
1.00E+02	1.20E+01	0.00E+00	0.00E+00	8.80E+01	0.00E+00	0.00E+00	1.00E+02	0.56	0.88	0
1.55E+00	5.50E-01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	1.55E+00	0.677445617	0.645108766	0
7.10E+01	1.20E+01	0.00E+00	0.00E+00	8.80E+01	0.00E+00	0.00E+00	1.00E+02	0.415	0.88	0
57.51670873	**8.1833754**	**0**	**0**	**59**	**0**	**0**	**67.1833754**	**0.550815206**	**0.801702922**	**0**
1.00E+02	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	1.00E+02	0.5	1	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	1.00E+02	0.5	1	0
100	**0**	**0**	**0**	**100**	**0**	**0**	**100**	**0.5**	**1**	**0**
4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.04	0	0
1.00E+02	3.40E+01	0.00E+00	0.00E+00	5.25E+01	0.00E+00	0.00E+00	1.00E+02	0.67	0.525	0
1.00E+02	6.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.53	0	0
1.00E+02	3.40E+01	0.00E+00	0.00E+00	5.25E+01	0.00E+00	0.00E+00	1.00E+02	0.67	0.525	0
4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.04	0	0
2.30E+01	4.40E+01	0.00E+00	0.00E+00	4.30E+01	0.00E+00	0.00E+00	1.00E+02	0.335	0.43	0
55.16666667	**21**	**0**	**0**	**24.66666667**	**0**	**0**	**100**	**0.380833333**	**0.246666667**	**0**
240.55	5.50E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	480.55	0.250858391	0	0
5.86E-01	0.00E+00	0.00E+00	0.00E+00	0.0103	0.00E+00	0.00E+00	1.00E+00	0.2928	0.0103	0
5.86E-01	0.00E+00	0.00E+00	0.00E+00	3.30E+01	6.70E+01	1.00E+00	1.00E+02	0.002928	0.33	0.67
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
85.4303	**25.1375**	**0**	**0**	**8.252575**	**16.75**	**0.25**	**170.3875**	**0.386646598**	**0.085075**	**0.1675**

Cold-Formed Aluminium Sheet for Outdoor Use	Volume	0.000408163	613200	6.39E+00	0.00E+00	6.91E-03	-4.44E+00
Concrete roofing tiles and fittings	Volume	0.065	438000	1.93E+02	0.00E+00	7.30E+00	-3.61E+00
Roof tiles	Volume	0.065	350400	2.97E+02	0.00E+00	0.00E+00	0.00E+00
Roof tiles			**394200**	**2.45E+02**	**0.00E+00**	**3.65E+00**	**-1.81E+00**
Eos Steel Frame	Volume	7.85	525600	2.07E+00	0.00E+00	3.44E-02	-8.18E-01
Hot Rolled Structural and Rail	Volume	7.85	350400	3.32E+03	0.00E+00	6.92E+00	-2.10E+03
Reusable Steel	Volume	7.85	525600	4.66E+01	0.00E+00	3.25E+01	0.00E+00
Steel Beam	Volume	7.85	350400	7.60E+02	0.00E+00	2.73E+01	4.26E+01
Steel Structural Hollow Sections	Volume	7.85	876000	3.06E+03	0.00E+00	1.13E+01	-1.48E+03
Steel Frame			**525600**	**1.44E+03**	**0**	**1.56E+01**	**-707.6436**
13mm-Glazed Rebated Door	Area	1	350400	1.22E+02	0.00E+00	1.29E+00	-2.80E+01
40mm-Glazed Door	Area	1	350400	2.15E+02	0.00E+00	4.24E+00	-3.43E+01
Steel Profile Door	Area	1	350400	1.25E+02	0.00E+00	4.46E+00	-2.23E+01
Glazed Door			**350400**	**1.54E+02**	**0.00E+00**	**3.33E+00**	**-2.82E+01**

3.02E-02	0.00E+00	3.05E-05	-2.26E-02	2.06E-03	0.00E+00	7.12E-06	-1.44E-03	1.74E-10	0.00E+00	3.78E-16	-6.18E-11
4.75E-01	0.00E+00	5.10E-02	-3.01E-02	2.49E-02	0.00E+00	3.39E-04	-7.84E-04	7.19E-06	0.00E+00	1.28E-06	-3.70E-07
4.70E-01	0.00E+00	0.00E+00	0.00E+00	5.00E-02	0.00E+00	0.00E+00	0.00E+00	5.21E-09	0.00E+00	0.00E+00	0.00E+00
4.73E-01	**0.00E+00**	**2.55E-02**	**-1.51E-02**	**3.75E-02**	**0.00E+00**	**1.70E-04**	**-3.92E-04**	**3.60E-06**	**0.00E+00**	**6.40E-07**	**-1.85E-07**
9.72E-03	0.00E+00	3.66E-04	-3.18E-03	1.03E-04	0	1.67E-06	-3.31E-05	1.63E-07	0.00E+00	5.27E-09	-2.20E-08
7.81E+00	0.00E+00	2.87E-02	-1.88E+00	9.40E-01	0.00E+00	5.26E-03	-3.31E-01	2.47E-12	0.00E+00	2.86E-14	-4.89E-13
2.76E-01	0.00E+00	1.84E-01	0.00E+00	3.60E-02	0.00E+00	3.50E-02	0.00E+00	6.54E-06	0.00E+00	2.87E-06	0.00E+00
4.01E+00	0.00E+00	3.28E-01	1.66E-01	4.37E-02	0.00E+00	1.65E-03	1.71E-03	8.40E-05	0.00E+00	4.58E-06	1.14E-06
7.99E+00	0.00E+00	5.85E-02	-3.30E+00	4.48E-04	0.00E+00	6.53E-06	-8.38E-04	4.49E-09	0.00E+00	1.66E-14	3.23E-12
4.02E+00	**0**	**1.20E-01**	**-1.003436**	**2.04E-01**	**0**	**8.39E-03**	**-0.06603222**	**1.81E-05**	**0**	**1.49E-06**	**2.23601E-07**
4.34E-01	0.00E+00	8.75E-03	-1.10E-01	1.50E-02	0.00E+00	2.25E-04	-3.80E-03	1.32E-05	0.00E+00	2.19E-07	-1.45E-06
7.52E-01	0.00E+00	2.82E-02	-1.34E-01	2.33E-02	0.00E+00	7.05E-04	-4.51E-03	2.85E-05	0.00E+00	7.73E-07	-1.98E-06
1.05E+00	0.00E+00	8.50E-03	-1.85E-01	4.90E-03	0.00E+00	3.74E-05	-1.49E-03	1.21E-05	0.00E+00	1.79E-07	-1.56E-06
7.46E-01	**0.00E+00**	**1.51E-02**	**-1.43E-01**	**1.44E-02**	**0.00E+00**	**3.22E-04**	**-3.27E-03**	**1.80E-05**	**0.00E+00**	**3.90E-07**	**-1.66E-06**

1.00E+02	1.00E+01	0.00E+00	0.00E+00	9.00E+01	0.00E+00	0.00E+00	1.00E+02	0.55	0.9	0
1.00E+02	0.00E+00	0.00E+00	0.00E+00	1.00E+02	0.00E+00	0.00E+00	1.00E+02	0.5	1	0
1.00E+02	1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+02	1	0	0
1.00E+02	**5.00E+01**	**0.00E+00**	**0.00E+00**	**5.00E+01**	**0.00E+00**	**0.00E+00**	**1.00E+02**	**0.75**	**0.5**	**0**
3.33E+01	5.00E+00	0.00E+00	0.00E+00	9.50E+01	0.00E+00	0.00E+00	1.00E+02	0.1917	0.95	0
7.50E+01	1.00E+01	0.00E+00	0.00E+00	9.00E+01	0.00E+00	0.00E+00	1.00E+02	0.425	0.9	0
4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	9.60E+01	1.00E+00	1.00E+02	0.04	0	0.96
1.00E+02	5.00E+00	0.00E+00	0.00E+00	9.50E+01	0.00E+00	0.00E+00	1.00E+02	0.525	0.95	0
1.00E+02	1.50E+01	0.00E+00	0.00E+00	8.50E+01	0.00E+00	0.00E+00	1.00E+02	0.575	0.85	0
62.468	**7.8**	**0**	**0**	**73**	**19.2**	**0.2**	**100**	**0.35134**	**0.73**	**0.192**
7.50E+01	5.00E+00	0.00E+00	0.00E+00	9.50E+01	0.00E+00	0.00E+00	1.00E+02	0.4	0.95	0
8.10E+01	26	0.00E+00	0.00E+00	1.90E+01	0.00E+00	0.00E+00	1.00E+02	0.535	0.19	0
1.00E+02	7.50E+01	0.00E+00	0.00E+00	1.25E+02	0.00E+00	0.00E+00	4.00E+02	0.21875	0.3125	0
85.33333333	**35.33333333**	**0**	**0**	**79.66666667**	**0**	**0**	**200**	**0.384583333**	**0.484166667**	**0**