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Single building analysis and comparison of alternative scenarios

Infrastructural and Environmental Engineering, ACEX30-19-15

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MASTER'S THESIS 2018

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ACEX30-19-15 - Master's thesis in Architecture and Civil Engineering

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Evaluation of Circular Economy design principles by Material Flow Analysis
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Abstract

The building industry consumes around 40% of extracted materials globally, while construction and demolition waste is the major source of waste in OECD counties. Traditional linear economy (make, use, dispose) has in recent decades triggered concerns which has inspired circular economy - a system which prolongs product and material service lifetime, and is intentionally designed to be restorative or regenerative at end of life.

The purpose of the study is to analyse changes within material flow when circular economy design principles are implemented into a specified house layout. The object of study is a villa in Cairns, Australia. The initial scenario (original villa design) is compared to scenarios where circular economy design principles are used to select the major components of the house to construct the same layout. Evaluation of how much circular economy design principles can influence is calculated by Material Flow Analysis in the comparative unit kg. Whereas Material Flow Analysis is commonly applied on a national level, regional and local cases are unusual.

Two alternative scenarios of the building are created based on the design strategies of circular economy for built environment; Building in Layers, Designing-out waste, Design for adaptability, Design for disassembly and Selecting materials. The first scenario, Alternative 1 is where alternative components are used to create the same layout and lifetime as initial scenario. The second scenario, Alternative 2 is using the new components and pro-longing the lifetime (which generates further refurbishments during the usage stage). The initial scenario has a Circular Economy(CE) ratio of 49%, Alternative 1 has a ratio of 70%, and Alternative 2 has a ratio of 60%. It should be noted that materials downgraded and recovered for energy purposes are included into the recycling category, which means a decreased value of these materials when re-purposed. Compared to initial scenario, the CE ratio for Alternative 1 was 21% higher while decreasing the total used mass with 55.5%.

Sammanfattning

Byggindustrin konsumerar ungefär 40% av utvunna råmaterial globalt, samtidigt som bygg- och rivningsavfall är den störta avfallskällan i OECD-länder. Den traditionella linjära ekonomin (skapa, använd, släng) har under de senaste decennierna blivit ett bekymmer som har inspirerat cirkulär ekonomi - ett system som förlänger produkt- och materiallivstiden och är avsiktligt utformad för att vara återupprättbar eller regenerativ vid slutet av användningen.

Målsättningen med denna studien är att jämföra skillnaderna i materialflöden när principerna av cirkulär ekonomisk design implemneteras till en specifik byggnadsstruktur. Byggnaden som undersöks är en villa i Cairns, Australien. Ursprungsscenariot, där byggnaden är konstruerat med traditionella komponenter, är jämfört med scenarios där komponenterna är valda med hjälp utav design principer enligt cirkulär ekonomi. Påverkan av design principerna utvärderas med hjälp utav materialflödesanalys som sammanställer mängder material i kg som konsumeras under bygnadens livstid. Materialflödesanalys tillämpas vanligen på nationell nivå, regionala och lokala fall är ovanliga.

Två alternativa scenarier av byggnaden skapas utifrån designstrategierna för cirkulär ekonomi för byggindustrin; Byggna i lager, Utformning av avfall, Design för anpassningsförmåga, Design för demontering och Materialval. Det första scenariot, Alternativ 1, är där alternativa komponenter används för att skapa samma layout som ursprungsscenariot. Det andra scenariot, Alternativ 2, använder samma nya komponenter och förlänger livslängden (vilket genererar ytterligare renoveringar under användningsfasen). Det ursprungliga scenariot har ett Cirkulär Ekonomi (CE) -värde på 49 %, alternativ 1 har ett värde på 70 % och alternativ 2 har ett värde på 60 %. Det bör noteras att material som nedgraderas och återvunnits i energisyfte ingår i återvinningskategorin, vilket innebär ett minskat värde av dessa material när de återupptas. Jämfört med ursprungliga scenariot var CE-förhållandet för Alternativ 1 21 % högre medan den totala använda massan minskade med 55,5 %.

Keywords: circular economy, recycling, building materials, building industry, material flow analysis, MFA, off-site production, construction, environment, landfill, modular

Contents

1

Introduction

1.1 Background

The building industry is found to be the greatest consumer of raw materials in OECD countries by the OECD Green Growth Studies, 2015. Only a fraction of the materials is recycled, although the construction and demolition waste is the greatest waste stream

Cheshire D. (2016) states that the building industry consumes approximately 40% of the worlds extracted materials. He describes that the current usage of resources in the building industry results in loss of a valuable material stock. If the consumption would be less wasteful, the demand for extraction of new raw materials would be reduced. Extraction has become more difficult and energy demanding than a century ago and the building materials are not infinite resources. Meanwhile, the global population is growing and the middle class is predicted to double in size by the year 2030, increasing the demand for new buildings.

Cheshire D. (2016) explains that the wastefulness of the building industry is connected to the linear economy approach. Described by Ellen MacArthur Foundation, 2016, the basics of the traditional linear economy are: *take, make and dispose*, see figure 1.1. Chehire clarifies that embodied in the building industry, the linear economy means; extracting raw materials, constructing a building to fulfill its purpose, while the demolition process becomes someone else's project in the future.

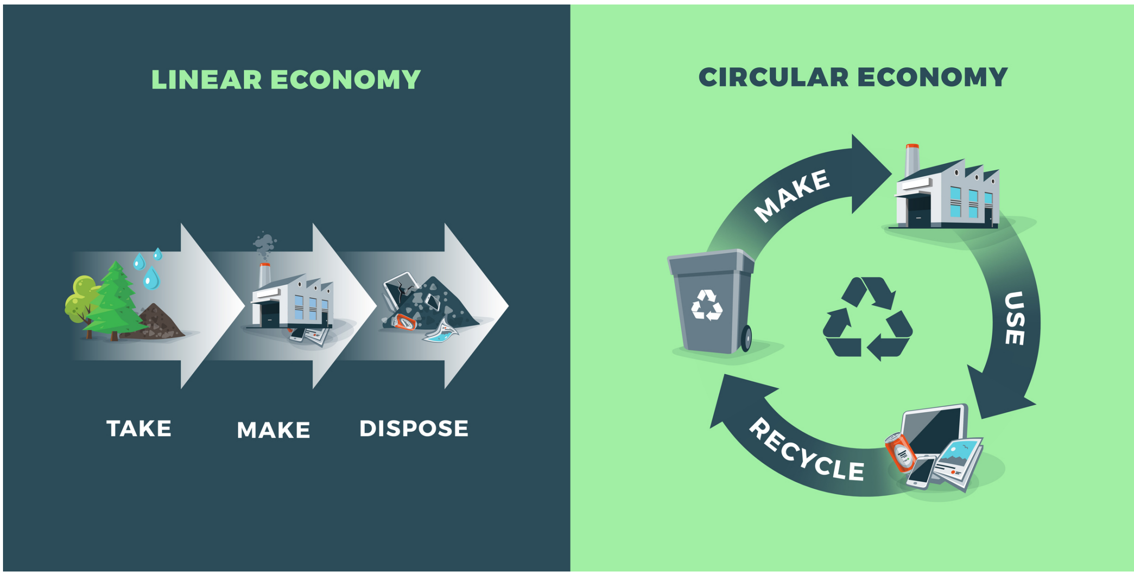


Figure 1.1: Visualisation of linear economy vs circular economy

Growing environmental concerns have inspired a more sustainable model. The traditional linear economy approach is challenged by the circular economy, see figure 1.1. As described in the report "Towards the circular Economy: Economic and Business Rationale for an Accelerated Transition":

"A circular economy is an industrial system that is restorative or regenerative by intention and design" - Ellen MacArthur Foundation, 2013

As explained by Zimmann et. al, (2016), following the principals of circular economy is most effective when involving them from the beginning of design creation, of which the major part is set by the architects[**?**]. Curtin (2014) explains that it is well known that waste avoidance is most efficient when implemented by a front-of-pipe approach, meaning tackling the sources and initial processes of waste generation instead of focusing on methods to reduce or sort already created waste. In spite of this, there is little empirical evidence on how to avoid waste generation in the first place through design changes and process improvements. He states "The front-of-pipe solutions through design interventions are suggested to offer the greatest cost savings to a project, as waste avoidance offers greater savings than re-use or recycling."

1.2 Aim and Objectives

"The essence of circular economy lies in designing goods to facilitate disassemble and re-use, and structuring business models so manufacturers reap rewards from collecting and refurbishing, re-manufacturing redistributing the products they make"
- Ellen MacArthur Foundation, 2013

The aim of this masters thesis is to analyse changes in material flow when the components within a common residential house is changed to fit the design principals of circular economy. A case study villa will be analyzed at the design stage at an architecture firm, tracking the materials required to create the layout. The object of interest is a typical residential building for Queensland, Australia, taken from an actual project at McElroy Morrisson Pierce Architects. This villa's theoretical material usage and waste quantities will be analysed during production(partly), construction, usage and end of life. The Material Flow Analysis defines flows of masses and waste creation during the house's lifetime, creating a transparent process giving insight throughout the lifetime of the building. The material flows of the initial building are analysed for the set lifetime of the building, from production to demolition and the feed of material back into the system through recycling and reuse. The alterative scenarios are created by different material inputs, which all build up the same house layout. The new input materials and components are selected by the principles of circular economy. The different scenarios are evaluated by tracking the weights of the construction materials used and replaced during the lifetime of the building. The results are compared by visualising the quantities of materials for different stages of the buildings lifetime. The objectives for this project are:

- Study the composition of the case study building and create a favorable simplification to be used in Material Flow Analysis.
- Inspired by circular economy, create an alternative composition of the case study building while keeping the original layout.
- Track and compare the material flows within the lifetime of a building to create a transparent picture of the processes.
- Determine the impact circular economy design strategies with the method of Material Flow Analysis, by comparing the masses in the comparative unit KG.

1.3 Scope

Bellstedt C (2015) describes that Material Flow Analysis is commonly used for national investigations, while regional or local studies are unusual. This masters thesis combines uncommon applications of the circular economy theory and the tool Material Flow Analysis focused on a single residence. Most case studies of circular economy in the built environment which can be found in literature are based on creating a new concept for specially constructed buildings with unique purposes, like a demonstration models or modern office-buildings. This approach tackles the problem from a different angle, assuming that the traditional villa layout satisfies the residents, and instead focuses on altering the input materials and building processes. The ambition to create a real-life scenario, where a common house layout can be built while using less material and generating less waste. This study focuses on design approaches of circular economy, and will not involve life cycle analysis of the materials/components. The main design of the villa is set by the architectural firm and will not be altered, only the components it is built up with. The study analyses the material flows of a commonly accepted layout, traditional refurbishment patterns and the possibilities for improvement for the conditions set. The comparative unit is the weight of materials used, while the usage is tracked during the lifetime of the building. The alternative scenario, where other materials are used to build the same layout, is set to be a realistic solution with sufficient living standards adapted for the case study.

2

Theory

The theory chapter begins with a summary of the general design strategies of circular economy, following by strategies specialised for the building industry. The design strategies are important to create guidelines to determinate if material/component selections for the alternative scenario are following circular economy design strategies.

2.1 General circular economy design strategies

The report *"Circular economy – From review of theories and practices to development of implementation tools"* by Kalmykovaa Y et al. 2017, summarizes modern global literature and provides the circular economy strategies database. This is an general literature study, not specified for the building industry. The design strategies are divided into nine different categories: materials sourcing, design, manufacturing, distribution and sales, consumption and use, collection and disposal, recycling and recovery, materials sourcing(2), re-manufacture and circular inputs. All of the strategies below in this chapter 2.1 are from the previously mentioned report by Kalmykovaa Y et al, 2017.

Customization/Made to order
The product is optimized especially for the given purpose, which can decrease the usage of materials and waste generation. A satisfied customer will value the product and maintain it, which prolongs the life of the product and reduces waste. The clients satisfaction with the product is important to create continuing business and loyalty.

Design for disassembly/recycling
To keep the product valuable, it is important to make the reuse and recycling as easy as possible. Therefore, the component shall be easy to dismount as detach from others to keep it in a loop.

Design for modularity
During the lifetime of the product, it's purpose can be changed. If the product is easy to maintain, keep up to date and is flexible for improvement - more value is added to it and the chance of having a longer usage time is increased.

Eco design
Analyze and decrease the environmental impact the product will have during it's whole lifetime. Some products might seem environmental friendly, but affect the environment in unexpected ways.

Reduction
Minimize the quantities of the materials used to create the product, as well as harmful substances which can have a massive impact even in smaller quantities.

2.2 Circular economy design strategies for the built environment

The book *Building Revolutions, Applying the circular economy in the built environment* by Cheshire D, 2016, describes the design strategies customised for the building industry. As can be seen in figure 2.1, most effective design strategy is to retain the existing structures while the least effective is recycle/compost (transportation and creation of new component devours energy, time and materials). By using the design strategies of building in layers, designing out waste, design for adaptability, design for disassembly and selecting materials, more flows will stay within the inner loops and less will go to the outer loops. Landfill is not included as an alternative in figure 2.1, since it is not seen as a strategy but as the least desired outcome. Nevertheless, landfill is an alternative end-destination of a product, and perhaps can be seen as failure of circularity.

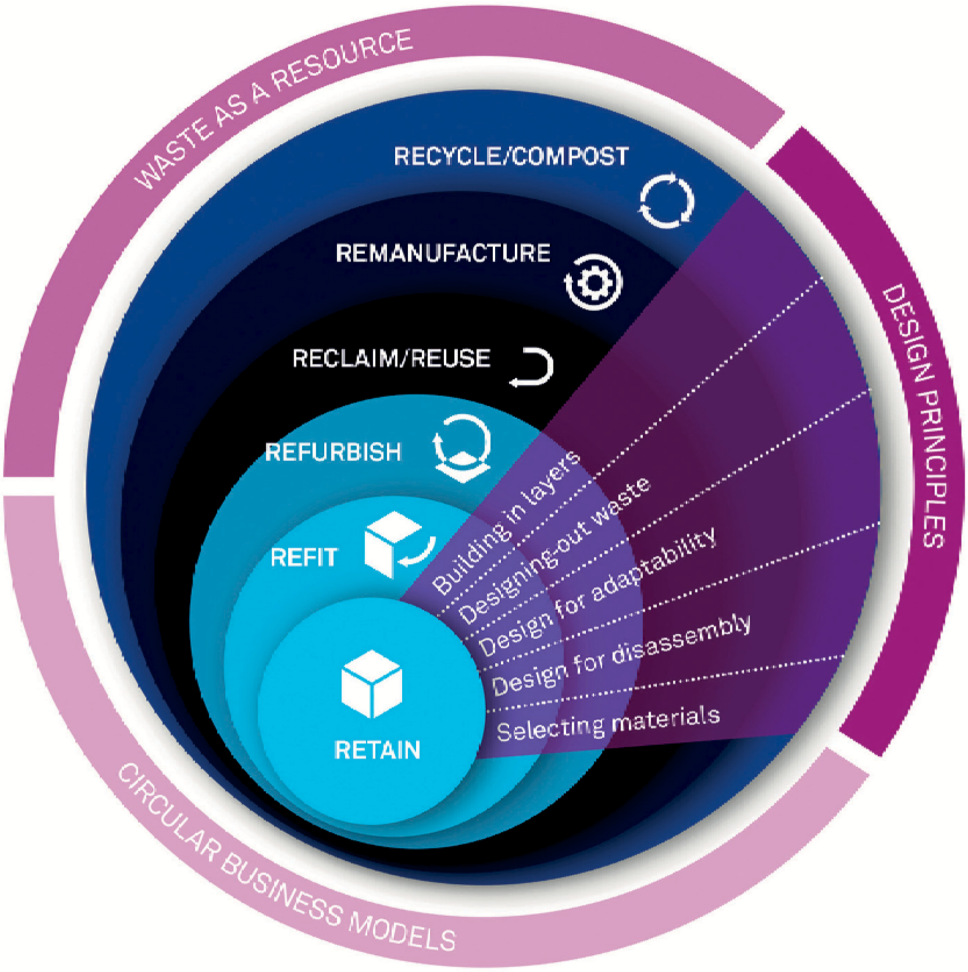


Figure 2.1: Design strategies where the inner circles is most important to prioritise. Picture taken from Building Revolutions by Cheshire D, 2016, p. 32

2.2.1 Building in Layers

Cheshire D, 2016, describes that dividing a building into different layers enables an overview of the connections and dependencies of the different components within the building. The layers have different purposes as well as different length of life. The model in figure 2.2 is of course a simplification of the complex and varying composition that a building is, however very useful to sort components into layers with specified purposes. The skin the protective outer layer of the house, a shelter for the inner layers displayed in yellow colour. The layer structure is the “backbone” of the house, supporting the whole construction, displayed in blue. Space is the interior layout of the building, for example interior walls and floors displayed in green. According to circular economy, the connection between components with different lifespans should be avoided since the layers are replaced or refurbished during different occasions. For example, in case the structure would fail, the whole house will most probably fall apart, therefore all layers are dependent on the layer structure. Creating detached layers within a building simplifies repair, recycling, enhances the demolition process, decreases the risk of not using the whole potential of the material and reduces overall material consumption.

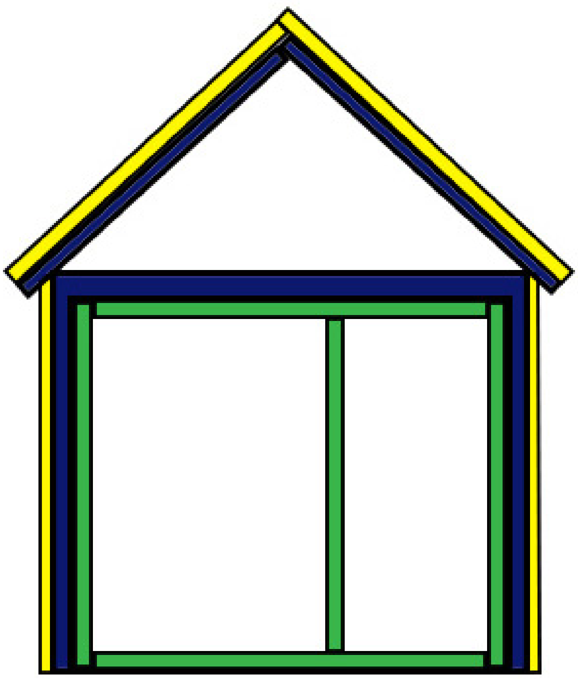


Figure 2.2: Visualisation of different layers for a building. Yellow represents the layer **skin**, blue represents the layer **structure** and green represents the layer **space**. Picture drawn by Marina M. following description by Dave Cheshires book "Building Revolutions, Applying the circular economy to the built environment", 2016.

ARUPs full-scale prototype *The Circular Building* is an excellent example of a circular economy construction built in layers, Williams J, 2017. Majority of the layer structure consists of steel beams connected with detachable clamps (making reuse possible without modifying the beam connections). Since all components are detachable, there is no permanent connection between the layers, which enhances refurbishment, deconstruction, reuse and recycling. The walls are prefabricated and demountable structural insulated panel wall system. Many components were recycled or reused, like the acoustic wall system made of plastic bottles. Some of the components were fully biodegradable, like the mycoboard insulation, which consists of fungi. The components are pre-fabricated, which minimises on-site waste, overall waste generation, and accelerates the assemble process, Archello, 2018. Every item in the house is listed and tagged, to provide essential information for future purposes. All different components are set to be used to the full potential during the house lifetime or be reused when the life ends.

Figure 2.3: The Circular Building, picture taken from Make Wealth History, 30th of July, 2018

2.2.2 Designing out waste

The most optimal circular economy design does not generate waste at all, Cheshire D, 2016. Instead, the used components are getting a new life and new purposes, like nutrient flowing through a biological system. The different strategies to design-out waste are preserving existing buildings, decrease waste generation during construction, include reused or recycled materials and use lean design principles.

One strategy by Cheshire D, 2016, is prioritizing the already existing building and components instead of constructing new ones, this reduces both waste creation and energy consumption. Retaining what already is produced saves virgin material, energy and transportation. Materials considered waste can be given new functions by clever design approach.

55 Baker Street, London, is a great example of creative refurbishment instead of the initial plan - demolition of the existing building, made by Make Architects, 2018. The 1950s four blocks office buildings has been joined by a modern glass facade - saving excessive amount of material and creating luxurious combination of office spaces, cafés and accommodation.

Figure 2.4: 55 baker street before and after the refurbishment, picture taken from Make Architects, 2018

Another strategy described by Cheshire D, 2016 is to focus on the waste which is generated during the construction process. There are national standards which calculates an approximate amount of waste generated by each material during on-site construction in the building industry, but in some cases are found to be underestimating the actual volumes. *Wastage rate report*, 2008, by S Zakar, is analysing the actual waste volumes compared to the predicted ones in UK. Three construction sites (A,B,C) were analysed to list the masses of waste rates, compare them to the estimated waste amount set by standard waste rate figures and calculate the difference in costs. Site A includes 35 steel framed houses and 26 brick and block houses. Site B includes 15 insulated concrete formwork houses and 20 brick and block houses. Site C includes 15 timber framed houses. The collection of data was measured by tracking the amounts of the imported construction products and subtracting the waste rates. The figure 2.5 lists the used construction products used on site, minimum quantity specified is the specific amount within the building when it is constructed, waste is the actual amount of waste generated in case study, minimum quantity ordered is the volume delivered on-site, GG is the Green Guide (GG) to Specifications is the assumed waste created during construction to cover for off-cuts, over-ordering, breakage and theft, and the measured waste rate is defining how much waste was generated compared to what was delivered on-site (minimum on-site delivery). The conclusion is that in all three sites, the total volume of waste produced was approximately twice the size as the estimated volume by standard wastage rate units! The main volumes came from plasterboard and render. The major reasons for waste production were set to be (from greatest to smallest): methods of work - off-cuts, over ordering, unsuitable storage/materials exposed to unsuitable weather conditions, rework done due to unclear drawings/design specifications. The monetary loss due to underestimation of waste production ended up to: Site A- £ 35,455, Site B £27,518 and Site C - £14,413 (where the majority of losses was due to material costs).

Construction Products	Minimum Quantity specified (m3)	Waste (m3)	Minimum Quantity Delivery (m3)	GG wastage rate (%)	Measured wastage rate (%)
Mortar	204.9	35.5	240.4	6.7%	14.8%
Bricks	565.4	67.2	632.6	5.0%	10.6%
Concrete roof tiles	36.5	13.3	49.8	5.0%	26.7%
Concrete blocks	855.9	67.0	923.0	5.0%	7.3%
Mineral wool	1,055.0	22.8	1,077.8	5.3%	2.1%
Polystyrene (floor)	111.0	5.0	116.0	10.0%	4.3%
Polyurethane insulation panel	166.8	33.9	200.7	10.0%	16.9%
Plaster	105.9	22.7	128.6	5.0%	17.7%
Plasterboard	229.8	107.8	337.6	5.0%	31.9%

Construction Products	Minimum Quantity specified (m3)	Waste (m3)	Minimum Quantity Delivery (m3)	GG wastage rate (%)	Measured wastage rate (%)
Mortar	132.27	14.3	146.57	6.70%	10.0%
Render	10.35	10.58	20.93	5%	51.0%
Bricks	209.57	67.2	276.77	5%	24.0%
Roof tiles	98.04	13.3	111.34	5%	12.0%
Concrete blocks	922.62	67.04	989.66	5%	7.0%
Mineral wool	647.39	24.41	671.8	5.25%	4.0%
Polystyrene (floor)	75.09	15.27	90.36	10%	17.0%
Polar wall insulation	185.5	27.81	213.31	10%	13.0%
Plaster	92.39	7.56	99.95	5%	8.0%
Plasterboard	74.66	69.12	143.78	5%	48.0%
Chipboard floor	29.83	9.6	39.43	8%	24.0%

Construction Products	Minimum Quantity specified (m3)	Waste (m3)	Minimum Quantity Ordered	GG %	Measured %
Mortar	65.79	6.16	71.95	6.7%	8.6%
Render	1.58	0.5	2.08	5.0%	24.0%
Screed	51.6	3.5	55.1	5.0%	6.4%
Bricks	168.42	30.05	198.47	5.0%	15.1%
Concrete tiles	11.72	1.68	13.4	5.0%	12.5%
Concrete blocks	224.26	13.67	237.93	5.0%	5.7%
Mineral wool	289.65	12.2	301.85	5.3%	4.0%
Polystyrene (floor)	53.77	5.3	59.07	10.0%	9.0%
Plaster	14.78	3.96	18.74	5.0%	21.1%
Plasterboard	82.69	37.75	120.44	5.0%	31.3%
Weather boarding	2.44	0.7	3.14	5.0%	22.3%

Figure 2.5: Waste generation for each site, A, B, C organised after the different construction products. Table taken from Wastage rate report, 2008

The study *Waste avoidance and reuse strategies for residential buildings in Australia* compares initial waste generation during a construction of a villa, compared to waste generation created when applying improved waste reducing strategies. The purpose of the study is to estimate the possible reduction in waste masses by applying a well planned waste strategy. Both villas has the same layout but a few materials choices has been changed. The project is a cooperation between The Centre for Design and Society (CfD+S) at RMIT University, Burbank Australia and the Housing Industry Association (HIA). The initial building is a typical 4 bedroom residential house of 212 m2. The different waste categories are; bricks and mortar, cardboard, carpet and underlay, cement sheet, concrete, mixed waste, isolation and sarking, metals, plasterboard, plastics, polystyrene, tiles (interior), tiles(roof), and timber.

A total of 9,126.1 kg waste was produced during the initial construction and all of it was sent to landfill. The waste distribution between the different components can be seen in figure 2.6 for both the initial and final house. A detailed analysis of the waste generation lead to creation of new design and waste management implementations: decrease of off-cuts by better design planning, alternative material selections for the roof (steel instead of concrete), non/acceptance of over supply. The most affected layer was skin, since the roof was changed and the plasterboard usage was optimized. The study does not cover the amount of materials put into the building, only the waste which was generated. The new villa with the implemented waste strategies reduced the total amount of waste by 72.4%. Only 30.8 kg waste was sent to landfill, while 2 347.9 kg was recycled and 144.5 kg was reused.

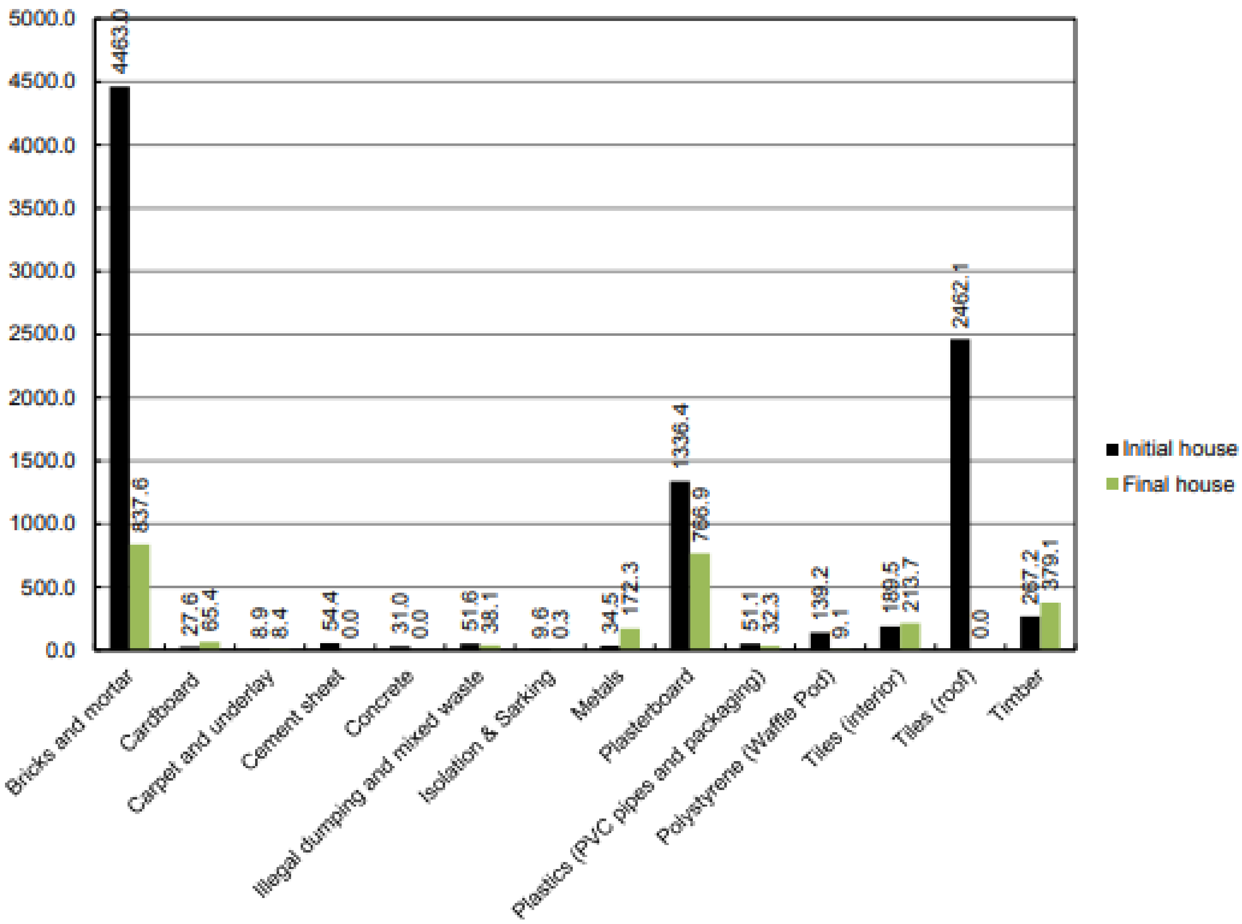


Figure 2.6: Waste rates created during the construction process, initial house construction waste compared to the final house construction waste when implementing improved waste strategies. The scale unit is kg. Picture taken from Waste avoidance and reuse strategies for residential buildings in Australia, 2014

Another strategy by Cheshire D, 2016 is to find ways to include materials considered to be waste to be used for new purposes. As previously told in chapter 2.2.1, parts of ARUPs The Circular Buildings acoustic wall is made of recycled plastic bottles. When possible, find ways to turn waste into resources.

The last strategy by Cheshire D, 2016, is to design-out waste is to use lean design principles. Minimize the amount of material used and simplify the production process. Analysing which materials are the most resource intensive is important to understand what can be improved and should be prioritised to preserve and maintain. The layer structure is often the most resource and energy consuming layer, while it has the longest lifespan. Reuse should be prioritised before recycling. It is often forgotten that recycling does create waste, energy consumption for the transformation and transportation costs. The building techniques used on site also affects the waste generation by for example off cuts and over supply. When selecting new materials and components, a waste generation investigation should be proceeded.

The ARUPs full-scale prototype *The Circular Building*, which was mentioned earlier, is also a great example of a house built with lean design principles. The house is built in layers, which simplfies further reuse of components. The structure is built in steel, which is a resource and energy consuming choice, but beneficial because the components is built to be easily reused and has a long lifespan. Creation of this component involves production, planning future usage of object and waste generation estimation according to lean design principles.

2.2.3 Design for adaptivity

A building usually has several different owners during its lifetime, Cheshire D, 2016. An adaptable building being able to serve different purposes is more likely to be retained and have a longer lifespan. Retaining an already existing building is the inner and most influential loop of the circular economy design strategies, as can be seen in figure 2.1. An adaptable building is easily refurbished, and therefore is easy to change the layout and dissemble. Prolonging a buildings lifetime saves material and energy

In the book by Steward Brandt: *How buildings learn: What happens to building after they are built?*, 1995, different strategies on how to create an adaptable building are presented. The basis is: Create a durable, strong structure, while keeping the finishes and interior adjustable and easy to repair. Keep the layout simple so it can fit for different purposes. Build in layers, to keep the components with different lifespan detached. A generous storey height gives more variations of possible usage for the building.

The Martini Hospital in Groningen is an excellent example of an adaptable building, described in case study by Zinwave, 2018. The focus of the construction has been on flexibility to meet the changing requirements of the health-care sector. The hospital complex is partly a renovated 38,000 sqm building, and the rest 58,000 sqm is a new construction. The essence of the design is the modular building blocks of 60x16m with adaptable functionality. The wall position are flexible and the floor area can be increased by facade extensions by approximately 10%.

2.2.4 Design for disassembly

Designing for disassembly means that the distinction between the layers is clear and that the components can be taken apart without getting harmed or harming other parts of the building, Cheshire D, 2016. If the disassembling process is simple, the chances increase for the component to be unharmed, reused and encourage the circularity of materials. It also created a more adaptable building. If the building can be constructed and being taken apart while keeping its functional qualities, it could even be moved in case the site is no longer available for the initial purpose.During an interview with Anton Demolitions in Cairns, 2017, the issue of designing the constructions for future disassembly was discussed. There is a connection between the complexity of disassembly and reuse/recycling. Demolition is commonly a man labor job, the different components are taken apart and analysed if recycling is possible by hand. If the deconstruction process is too complicated and time-consuming, it might not profitable. Some of the other expenses is transportation and storage space. Unfortunately, it is common that the most cost-effective choice is to tear the house down with a bulldozer and send off the material to landfill. The demolition process is often not appreciated by the neighboring community, so the client prefers the job done quickly. To do a proper control of the construction components, the demolition firm needs to have a fair amount of land for sorting and storing, which adds additional costs. Materials gathered from the demolition must be valuable enough to be worth the sorting and storage costs. Even fully functional components gets deposited of since they don't have a market demand. If the constructions are simplified to be easily disassembled, it would make the reuse and recycling easier. But other factors like storage, landfill policies in the area and economic value of components are also affecting this matter.

2.2.5 Selecting materials

The materials are divided into two main categories - technical and biological, Cheshire D, 2016. Technical materials are created by man through an industrial process, and should aim for being reused as much as possible. Recycling technical products should be a secondary alternative. Technical materials are generally harder to recycle at end of life, if a material cannot be reused a biological one may be a better choice. It is advised to match the component with the set lifetime for the component, or longer if it can be reused. Biological materials can be returned back to the biosphere without harming the environment, for example the mycoboard insulation mentioned in chapter 2.2.1. Avoid contaminating biological materials. When selecting the materials and components, avoid products which mixes the technical and biological materials. The more complex the merging of different materials within a special component, the more difficult is it to recycle. Some merging between biological and technical materials are permanently inseparable and should be avoided.

2.3 Material Flow Analysis

Material Flow analysis is a method that tracks the flows and stock of material within a well-defined system, Brunner P.H et al, 2016. Inspired by the laws of physics, material flow analysis can be simply described as *amount of what comes within set boundaries is equal to what comes out.* The matter going into a system is equal to what stays added with what comes out. By using this method, which is described in Brunners book "Handbook of Material Flow Analysis", flows over time can be detailed and make a structured analysis of the income and the outcome within specific boundaries. Material Flow Analysis can simplify a complex scenario by analysing the major components and flows, and thereby generate results to support decision making. MFA provides transparency but is limiting the scenario due to its simplicity. Creating a Material Flow Analysis model for this specific task will give information about what kind of changes can theoretically be expected when changing the major components within a building adapted to a circular economy approach.

No example of material flow analysis applied to a single building has been found.

3

Case study

A typical residential building designed by MMP Architects, Australia, has been selected for this study. The layout of the house and the waste management in area are applied to this study.

Figure 3.1: Cairns, Picture taken from the website TripAdvisor, 2017

3.1 House A

The building is named House A, it's a typical residential one-story 3-bedroom villa with an area of 120 sqm. A 3D model in Revit specifies material selection and volumes of the structure and skin layer of the house.

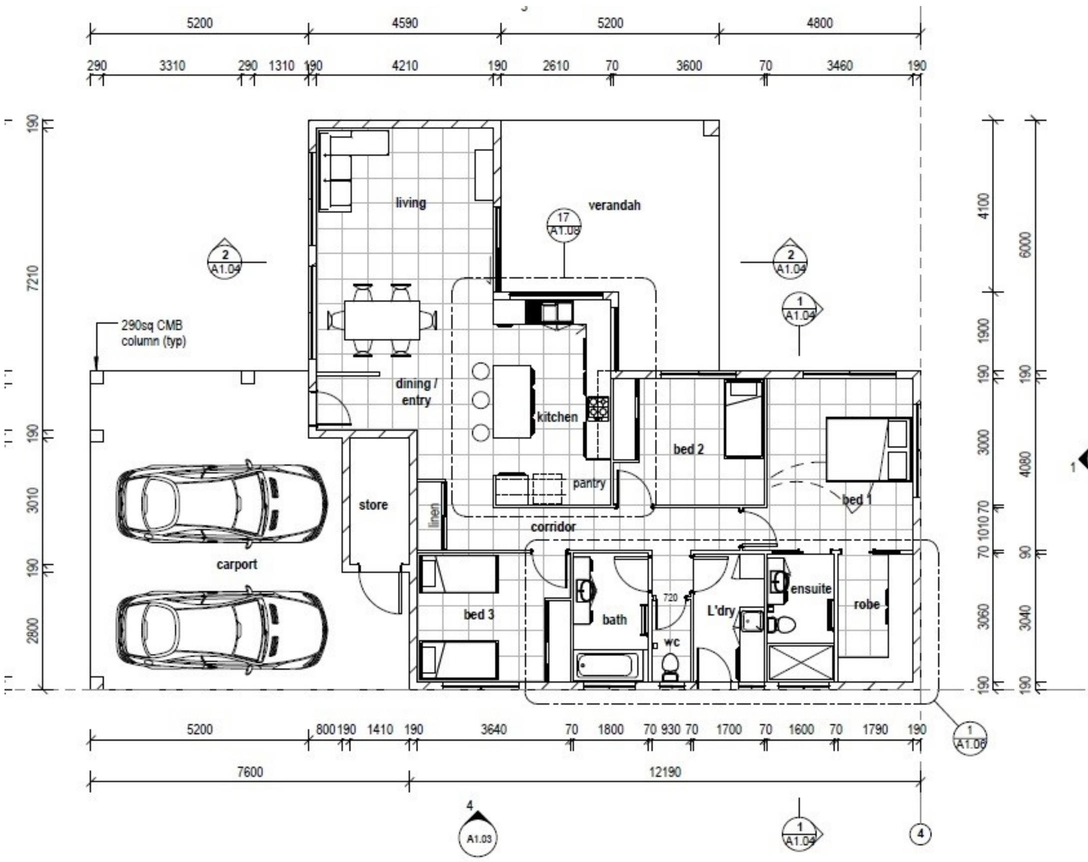
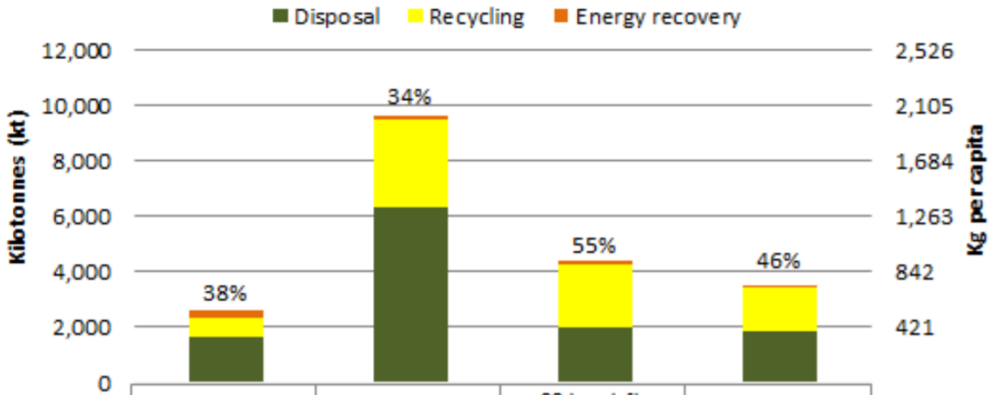


Figure 3.2: Floor Layout from the software Revit, use with permission from MMP Architects

3.2 Waste management of the study area

The building is planned to be built in Cairns, Queensland, a city with approximately 150 000 people in the state of northern Queensland (Carins Regional Council, 2018). The annual report of waste production in Australia year 2014-2015 is used to receive information about end-of-life destinations of construction waste. The Queensland area has a resource recovery rate at 38%, which is 20% below national average. The area has large transport distances which make recycling costly. The construction and demolition industry had a waste stream of 3,5 Mt annually where 46% was recovered (18% below Australian average). The top waste streams are fly ash, masonry materials and organics. The report points to a lack of resource recovery infrastructure in QLD. Figure 3.3 below visualises the waste generation in Queensland year 2014-2015 divided into the categories MSW (municipal solid waste), C&I (commercial and industrial), C&I excl fly ash (commercial and industrial excluding fly ash) and C&D (construction and demolition).



	MSW	C&I	C&I excl fly ash	C&D
Generation (kg/cap)	551	2,024	926	733
Generation (kt)	2,619	9,612	4,397	3,482
En recovery (kt)	247	133	133	10
Recycling (kt)	750	3,169	2,286	1,606
Disposal (kt)	1,622	6,310	1,978	1,866

'En recovery' means energy recovery. The stated percentages are the resource recovery rates = (energy recovery + recycling) / generation.

Figure 3.3: Waste generation of the state Queensland 2014-2015, Picture taken from Australian National Waste Report, 2016

4

Method

Different scenarios of the House A are created to be compared in terms of circularity. The initial scenario of House A, built with traditional materials, is compared to the alternative scenario - the same house layout but built with materials selected by using circular economy design principles, for the purpose of determining the impact of implementing circular economy design principles. Comparing the same layout presents the result of altering the material selection without changing the user experience; the desired design layout. The difference between the scenarios is calculated by level of circularity which is tracked by using Material Flow Analysis in the comparative unit kg. First the initial scenario of House A is analysed, the components set by the architecture firm are tracked and Material Flow Analysis is used to determinate the circularity. House A is divided into layers and material flow analysis is used to calculate the flows of materials throughout the lifetime of the system. Each component is tracked through the processes of off-site production, on site-construction, stock, and waste generation into different categories, creating a transparent process schedule. Then, the alternative scenarios are created with inspiration from design strategies for circular economy and the material flows between the different scenarios are compared. The method chapter contains a general step by step summary, which is followed by a more detailed explanation for each scenario where all the steps are thoroughly explained.

4.1 Methodology summarised step by step

The initial scenario, House A, is processed through step 1,2,3 which gives information about material flows and circularity of the initial scenario (calculation MFA). Following is the generation of alternative scenarios, Step 4, by selecting components and materials based on circular economy design principles. The alternative scenarios are then processed through the same steps 1,2,3 to calculate material flows and circularity. Step 5 provides the comparison between different scenarios to analyse the impact of implementing circular economy design principles.

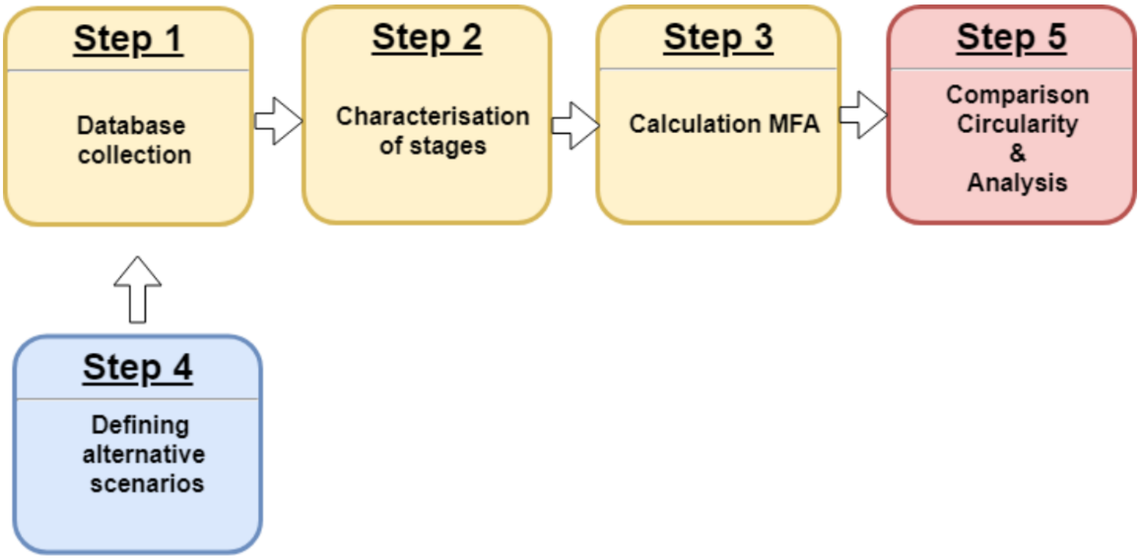


Figure 4.1: Flow chart of the major method steps.

4.1.1 Step 1 – Database collection

The building in selected scenario is divided into its major elements and components, then organised into layers according to circular economy theory, see figure 4.4 (MFA Excel spreadsheet Part 1) to follow the set up for initial scenario of House A. Excel is used as a tool to structure the Material Flow analysis. The column Elements lists the major volumes which can be defined by the Revit drawing in which the layout of house A is drawn. The components are a subgroup of an element. For example, a concrete slab is an element, while concrete and reinforcement are components which goes through different processes before they are joined together into an element. As can be seen in figure 4.4, the first column lists the elements like concrete slab, roof structure, interior walls, divided into the 3 different layers Structure Skin and Space. Second column from the right lists the components within the elements, which are materials merged into a component going through the same major production process. The comparative unit is set to kg and only the major components are included. Information is collected about each component including; weight of component/element, possibility to reuse, recycling rate, waste rate during production, waste rate during on-site construction and life expectancy in years.

4.1.2 Step 2 - Characterisation of stages

The information about the different components is implemented into the lifetime of the building. The different stages of the timeline is: Construction Stage, Usage Stage and End of Life, see figure 4.4 and 4.5. Construction stage defines the amount of materials to create the component and waste generated during the off-site production of the component (production of concrete in factory) and the on-site production (laying a concrete slab). Usage stage is a set lifetime that the building is used, and defines the amount of times some of the components will be replaced by analysing both refurbishment patterns and life expectancy for each component/element. On/off-site production material consumption is included for the replaced components. For example, the bathroom is a space which is frequently renovated and will consume material during the usage stage of the house. Material consumption for new tiles during on/off-site production will be included in usage stage. Usage stage shall have information if the component will be reused or not, when the component is replaced and if the components will be reused/recycled. Some components are replaced as an element while the recycling is proceeded for separate parts (see window, reused as element, but glass and aluminum recycling is separated, see figure 4.4 and 4.5, Layer Skin).The stage end of life means the building is taken down and defines what components will go to landfill, be recycled or reused.

4.1.3 Step 3 – Calculation MFA

This MFA model is built up to fit this study. Materials has a wide definition within the MFA, in this study materials are referred to as the components of the house. This MFA model is designed to track weight of material consumption related to selection of components. The processes are the transformations which components goes through before being installed and becoming part of the house. The processes are off-site production and on-site construction, and each process creates waste depending on the component/element. The house is referred to as the stock, being the inventory within the system. The boundaries of this MFA are set to start with production, construction, stock and then end with waste division into different categories (reuse, recycling/reproduction, landfill). The elements are structured into layers according to circular economy approach, to estimate and divide the influence each layer has on circularity.

The material consumption happens during different lifestages of the building (construction, usage, end of life) but the MFA model is not dependent on the timeline. MFA focuses on the processes that materials go through and visualises the total outcome of one building within one lifetime for set conditions. For example, the on/off site production exists in both usage and construction stage. When the bathroom is refurbished during the time "usage stage", material consumption will be included in processes of off-site production and on-site construction. The MFA tracks the total weight of materials consumed during different processes which can be tracked to specified layers or components.

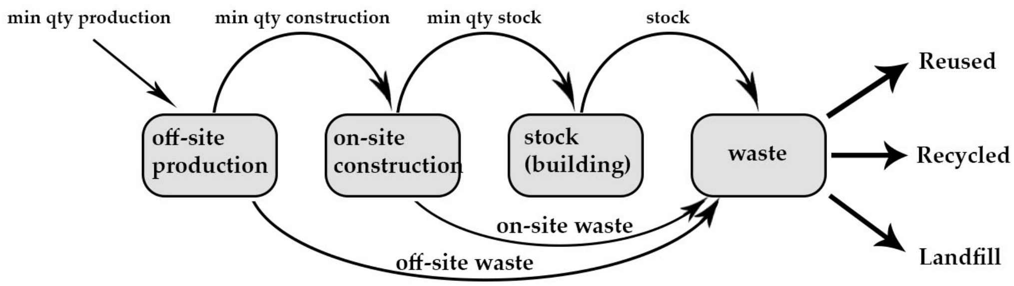


Figure 4.2: Visualisation of material flows calculated by this MFA.

4.1.4 Step 4 - Creation of scenarios

The alternative scenarios are created by selecting market-available products which are following the principals of circular economy. A set of criteria's is constructed to select acceptable products, which can be read about in chapter 4.3.1. The components are different but the same house layout is to be constructed for the same lifetime as House A. Two alternative scenarios are created. Alternative 1 is set to have a lifetime of 70 years, while Alternative 2 is extended to 140 years. This is to understand the changes in material flows when the lifetime is extended. Step 1,2,3 is repeated with the new scenarios.

4.1.5 Step 5 - Circular economy indicator

Step five is the comparison of the circularity as well as the masses of material flows within the different scenarios. The material flows are visualised in Sankey diagrams and compared. The level of circularity is defined by the formula:

$$\frac{(Recycled[\mathbf{kg}] + Reused[\mathbf{kg}]) \times years}{Total[\mathbf{kg}] \times years}$$

This is a straight on formula to represent the percentage of materials from the selected building building which will acquire the possibility to still be in circulation. It should be noted that this is a simplification. In reality recycling and re-usage is as well creating waste and consumes energy. The extent of how much waste and energy recycling and re-usage consumes is complicated to find, since it depends on national politics, consumer trends, the randomness of the users involved, and is different for each and every component, so it does not fit within the study. The formula clarifies the percentage of the house which will be disposed and materials lost.

5

Results

5.1 Initial scenario

This chapter describes the process in detail for the initial scenario.

5.1.1 Step 1 - initial scenario

Step 1 is database collection about the building, see figure 5.1. All the components and elements has been divided into layers structure, skin and space. The Elements and Components are listed on the left of the table divided into different layers. The information which must be obtained for each component is listed on top of the columns. The objective is to find the minimum quantity which of the different components/elements which are required to create the building. The minimum quantity of components and elements is defined by finding the volumes and areas in the Revit model. By finding volume or area of an element (for example concrete slab) and then finding information about the amount of components (concrete and reinforcement), the weight of the different components is obtained. Each and every component is analysed if it is reusable or not. Windows are an exception to be reused as the whole element (window) not as components (glass/aluminium). Futher, it is investigated how much waste is created during the processes of on-site construction and off-site production.For example, on-site construction with timber statistically generates 7% waste. This amount has to be added to the timber delivered for on-site. Further, the off-site production for timber boards actually generates 34% due to all the cut-off of the trees. This is later on used to calculate all the consumed masses to create the building. The house is assumed to be built by raw materials, not recycled ones. Life expectancy in years is found for every component/element. In the bottom of the excel sheet, there are summaries of the total masses as well as divided into the different layers Structure, Skin and Space.

Element	Component	STEP 1 - DATA COLLECTION								
Structure		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
concrete slab		55.40							100	
	reinforcement	0.14		8000	1084	no	0	0.3		0.82
	concrete	55.26		2400	132635	no	0.05	0.01		0.47
exterior wall		24.17							100	
	concrete blocks	11.06		2400	26542	no	0.07	0		0.47
	reinforcement	0.04		8000	344	no	0	0.3		0.82
	concrete filling	7.45		2400	17874	no	0.05	0.01		0.47
roof structure									84	
	timber skeleton	3.59		1000	3589	no	0.07	0.34		0.44
	steel details	0.07		8000	567	no	0	0.3	70	0.82
poles										
	steel	0.01		8000	99	yes	0	0.3	150	0.82
Skin		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
roof sheeting			304							
	colourbond stee	0.17		8000	1323	no	0.02	0.3	37	0.82
windows										
	windows		24	1m2 = 50.7 kg		yes			44	
	glass		20	14.96/m2	304		0	0.01		0.34
	aluminium		7	2800	904		0	0.76		0.82
wall exterior covering										
	Fibrecement		141	9.32 kg/m2	1315	no	0.25	0.01	60	0.46
	render	0.36	102	1700	605	no	0.05	0.01	53	0.47
Insulation										
	Fibreglass		163	0.92/m2	150	yes	0.1	0.12	100	0.46
Space		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
Interior walls		7.36								
	Plasterboard	2.68	143	540	1445	no	0.25	0.01	39	0.46
	Fibrecement	0.38	27	1500	568	no	0.25	0.01	70	0.46
	timber skeleton	0.84		1000	839	yes	0.07	0.34	70	0.44
	tiled wall		36	25.17 Kg/m2	906				100	
	tiles				889	no	0.05	0.02		0.47
	grout				17	no	0.15	0.01		0.47
ceiling cover										
	plasterboard	2.12		560	1187	no	0.25	0.01	39	0.46
floor finish										
	tiled flor		120	25.17 Kg/m2	3020	no			100	
	tiles		115		2994		0.05	0.02		0.47
	grout				27		0.15	0.01		0.47
	TOTAL				195300					
	STRUCTURE				182734					
	SKIN				4601					
	SPACE				7966					

Figure 5.1: Excel spreadsheet Part 1/5, general information of initial scenario.

5.1.2 Step 2 - initial scenario

Construction stage

A spreadsheet of all the elements and corresponding components is made for different stages during construction, see figure 5.2 for construction stage. The calculation begins with the known "in-situ" value, the weight of the component when the house is constructed. Adding the construction waste give info of minimum qty delivered to the construction site. For example, timber constructions generates 7% waste on-site. This is added to calculate the total required to be delivered to on site - which also is the minimum quantity which must be delivered by the off-site production. Off-site production, is as well generating waste which must be added for material delivery to the off-site production. For timber, to generate 3589 kg of timber construction, see 4.3, required 5848kg to be delivered to production site, see 4.4. Adding the minimum on-site construction with the off-site production waste gives the minimum qty delivered to production. The total waste generated during the construction stage is calculated and divided into what will be recycled or going to landfill.

min qty on-site construction = component weight + on-site construction waste
min qty off-site production = off-site prod waste + min qty on-site construction

Element	Component				CONSTRUCTION STAGE			
Structure		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
concrete slab								
	reinforcement	1084	0	1549	465	465	381	84
	concrete	139616	6981	141026	1410	8391	3944	4447
exterior wall								
	concrete blocks	28540	1998	28540	0	1998	939	1059
	reinforcement	344	0	491	147	147	121	27
	concrete filling	18815	941	19005	190	1131	531	599
roof structure								
	timber skeleton	3859	270	5848	1988	2258	994	1265
	steel details	250	0	357	107	107	88	19
poles								
	steel	99	0	141	42	42	35	8
Skin		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
roof sheeting								
	colourbond stee	1350	27	1929	579	606	497	109
windows								
	windows							
	glass	304	0	307	3	3	1	2
	aluminium	904	0	3765	2861	2861	2346	515
wall exterior covering								
	Fibrecement	1754	438	1772	18	456	210	246
	render	636	32	643	6	38	18	20
Insulation								
	Fibreglass	167	17	189	23	39	18	21
Space		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Interior walls								
	Plasterboard	1927	482	1947	19	501	231	271
	Fibrecement	757	189	764	8	197	91	106
	timber skeleton	902	63	1367	465	528	232	296
	tiled wall					69	32	37
	tiles	936	47	955	19			
	grout	20	3	20.20	0.20			
ceiling cover								
	plasterboard	1583	396	1599	16	412	189	222
floor finish								
	tiled flor					227	107	120
	tiles	3151	158	3215	64			
	grout	32	5	32	0.32			
	TOTAL	207028	12045	215460	8432	20477	11004	9473
	STRUCTURE	192606	10189	196955	4350	14539	7032	7507
	SKIN	5115	514	8605	3490	4004	3090	914
	SPACE	9308	1342	9900	592	1934	882	1052

Figure 5.2: Excel spreadsheet Part 2/5, construction stage of initial scenario.

Some of the elements are on-site produced of different components (example: components reinforcement and concrete are used to produce the element concrete slab on site, which creates on-site waste) while others are simply the pre-fab element installed (example: Windows are just installed pre-fab windows) not having a material loss during the installation, or (example: Ceiling made of plasterboard) pre-fab components installed becomes the element but loses mass during installation due to cuts and fitting.

waste recycle rate % = recycled mass
waste − recycled weight = landfill mass

The category recycled includes data for recycling, downcycling and recovering but is simply named recycled. Nothing is assumed to go to the reuse waste category, which is explained in the Usage Stage below. The reason is that no complete components are disposed during this stage, only the byproducts of component/element creation. The data for recycling/recovering or landfill is collected from governmental statistics of Australian National Waste Report, 2016.

The Usage stage
The usage stage defines material flows throughout the service life of the house. This stage requires information about the life expectancy of the components, as well as the previous information from the construction stage about the off-site production and on-site construction.

Number of replacements
The number of replacements depends on refurbishment patterns and lifetime, and is stated in figure 4.5. To make accurate assumptions about the refurbishment patterns, refurbishment statistics from Houze Magazine, Home Report, 2015, Australia. It is found that some components are changed due to life expectancy shortage, others because of refurbishing statistics due to aesthetic reasons (for example renovation of kitchen, not because the elements reached the end of life but to improve the looks). Some of the components will be replaced during the lifetime of the building and need production and installation of new components. To analyse the material flows it is important to evaluate how many times a component is replaced within the set time-span. It is assumed that the life expectancy for the house is 70 years, Vishnu Vijayakumar, 2016 , which is the set to the length of the usage stage . 58% of Australians renovated their home the last 10 years according to Australian Bureau of Statistics, 2002 . This equals a renovation every 17th year (100% of houses reovated by year 17). House A will be renovated 4 times during its lifetime (year: 17,34,51 and 68). Unfortunately, this does not give information about what kind of refurbishments are made. Refurbishment patterns for the usage stage was based on usage statistics, see appendix 1.1. Most popular renovation trends for Australia were analysed to get an assumption about what kind of renovations are carried throughout a typical life-time of a building to understand what kind of components are affected. The most common renovation types are: Living/family room, Kitchen, Guest bedroom, Master bathroom, Master bedroom. Assumptions were taken about what components are affected, see list at Appendix 1.2. This information affects the creation of a typical refurbishing scenario, but life expectancy was as well affecting the times of replacement. The most frequent replacement reason sets the times of replacement.

Some of the refurbishment statistics was described as different rooms, for example: "refurbishment of living room", see the left column in figure 4.5. This kind of refurbishment might affect the interior walls and floor but, it is uncertain what kind of components was exchanged. The refurbishments of living room, guest bedroom, master bedroom are assumed to affects floors and interior walls. Therefore, it is assumed that all of the finishes of the interior wall will be changed once during the house lifetime (70 years) while all the floors will be changed twice. Figure 4.4 includes the assumptions of the number of replacement of the different components during a span of 70 and 140 years.

Affected areas (as described in refurbishment statistics)	Number of replacements over 70 years	Number of replacements over 140 years	Affected component/element
Windows	1	3	Windows
Roof sheeting	1	2	Roof sheeting
Exterior cladding	1	2	Exterior fibreboard (House A) Tricoya extreme (Alternative 1,2)
Exterior paint/render	2	4	Render, House A
Living room	2	4	Interior wall *, Ceiling covering, Floor finish.
Kitchen	2	4	Interior wall *, Ceiling covering, Floor finish.
Guest bedroom	2	4	Interior wall *, Ceiling covering, Floor finish.
Bathroom	2	4	Interior wall *, Ceiling covering, Floor finish.
Master bedroom	1	2	Interior wall *, Ceiling covering, Floor finish.

Figure 5.3: Affected components by refurbishment patterns 70 and 140 years.

Min Qty off-site production is the total material usage from the action of production, multiplied by times the product is replaced, see figure 5.4. This defines the flow of materials during the usage stage to create new components. The off-site and on-site waste and weight of components are divided for further usage in the Material flow analysis where separation by action is required. The waste is analysed for on-site and off-site waste combined. During the usage stage the waste will include not only the bi-products of the off-site production and on-site construction of the new components, it will also include the disposed components/elements. Only components with lifetime left can be reused. Waste is therefore going into three different categories: reuse, recycle/recover and landfill. For example - under the category "times replaced" Timber inside the interior walls is set to be replaced 0.5 times, see figure 5.4. This means that during the buildings lifetime, half of the interior walls will be torn down and replaced to create new interior look. Therefore, material flows according to half of the materials consumption during construction will be consumed during usage stage, see figure 5.4 and 5.2. (1367kg see column min qty off-site production, row Space - timber skeleton, 5.2, times 0.5 equals 684 kg, 5.4. This is the total material consumption to create new interior walls timber skeleton. Further, information about the quantities of on/off-site waste, min quantities on site are found. Next figure 4.7 continues the usage stage database. The weight of the replaced component is set.

Element	Component						
Structure		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Min qty on-site	Waste on-site
concrete slab		0					
	reinforcement						
	concrete						
exterior wall		0					
	concrete blocks						
	reinforcement						
	concrete filling						
roof structure		0					
	timber skeleton						
	steel details	0					
poles		0					
	steel						
Skin		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Min qty on-site	Waste on-site
roof sheeting							
	colourbond stee	1	1929	579	1350	1350	27
windows							
	windows						
	glass	1	307	3	304	304	0
	aluminium	1	3765	2861	904	904	0
wall exterior covering							
	Fibrecement	1	1772	18	1754	1754	438
	render	2	1286	13	1273	1273	64
Insulation							
	Fibreglass	0	0	0	0	0	0
Space		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Min qty on-site	Waste on-site
Interior walls		0.5 min refurb.					
	Plasterboard	1	1947	19	1927	1927	482
	Fibrecement	1	764	8	757	757	189
	timber skeleton	0.5	684	232	451	451	32
	tiled wall	2	1950	39	1912	1912	100
	tiles						
	grout						
ceiling cover							
	plasterboard	1	1599	16	1583	1583	396
floor finish							
	tiled flor	2	6495	129	6365	6365	325
	tiles						
	grout						
	TOTAL		22497	3917	18580	18580	2052
	STRUCTURE		0	0	0	0	0
	SKIN		9058	3474	5584	5584	529
	SPACE		13439	443	12995	12995	1522

Figure 5.4: Excel spreadsheet Part 3/5, usage stage House A.

$$Waste \times 0.5 = Reused$$
$$(Waste - Reused) \times Recyclerate\% = Recycledweight$$
$$Waste - Recycledweight = Landfill$$

If the component is evaluated to be reused, it is assumed in this study that 50% of the amount will be reused and rest go to waste. This is to include the possibility of neglect due to time limit, economics or poor management during demolition. The statistics of recycling/recovering and landfill are based on the real facts where these kinds of problems influence the outcome, not all which can be recycled is recycled, therefor it is assumed to be more logic not to estimate best possible scenario. See table 4.3 which components are able to be reused, and 4.7 and 4.8 if they will be reused and what amounts are assumed.

Element	Component	USAGE STAGE					
Structure		Weight component	Tot. Waste	Reused this stage	Reused KG	Recycled	Landfill
concrete slab							
	reinforcement			no			
	concrete			no			
exterior wall							
	concrete blocks			no			
	reinforcement			no			
	concrete filling			no			
roof structure							
	timber skeleton			no			
	steel details			no			
poles							
	steel			no			
Skin		Weight component	Tot. Waste	Reused this stage	Reused KG	Recycled	Landfill
roof sheeting							
	colourbond stee	1323	1929	no		1582	347
windows							
	windows						
	glass	304	307	yes	152	53	102
	aluminium	904	3765		452	2717	1048
wall exterior covering							
	Fibrecement	1315	1772	no		815	957
	render	1209	1286	no		604	681
Insulation							
	Fibreglass	0	0	yes	not replaced	0	0
Space		Weight component	Tot. Waste	Reused this stage	Reused KG	Recycled	Landfill
Interior walls							
	Plasterboard	1445	1947	no		895	1051
	Fibrecement	568	764	no		352	413
	timber skeleton	420	684	yes	210	208	265
	tiled wall	1812	1950	no t		917	1034
	tiles						
	grout						
ceiling cover							
	plasterboard	1187	1599	no		735	863
floor finish							
	tiled flor	6041	6495	no		3052	3442
	tiles						
	grout						
	TOTAL	16528	22497		814	11931	10204
	STRUCTURE	0	0		0	0	0
	SKIN	5055	9058		604	5770	3136
	SPACE	11473	13439		210	6160	7069

Figure 5.5: Excel spreadsheet Part 4/5, usage stage House A.

End of Life

The stage of End of Life is less complex than the previous stages. The lifetime of the building, the stock, has come to an end. The stock becomes waste, which is divided into: reuse, recycle/recover and landfill, as previously described in usage stage. It is defined if the component can be reused based on the lifetime. For example, fibre-glass is a component with a life-expectancy of 100 years, at End of Life, it has 30 years to go, therefore it is assumed to be reused, see figure 5.6.

Element	Component				
Structure		**Reused this stage**	**Reused KG**	**Recycling**	**Landfill**
concrete slab					
	reinforcement	no		889	195
	concrete	no		62338	70296
exterior wall					
	concrete blocks	no		12475	14067
	reinforcement	no		282	62
	concrete filling	no		8401	9473
roof structure					
	timber skeleton	no		1579	2010
	steel details	no		465	102
poles					
	steel	yes	50	41	9
Skin		**Reused this stage**	**Weight reused**	**Recycling**	**Landfill**
roof sheeting					
	colourbond stee	no		1085	238
windows					
	windows	yes	604		
	glass			52	100
	aluminium			370	81
wall exterior covering					
	Fibrecement	no		605	710
	render	no		284	320
Insulation					
	Fibreglass	yes	75	35	41
Space		**Reused this stage**	**Weight reused**	**Recycling**	**Landfill**
Interior walls					
	Plasterboard	no		665	780
	Fibrecement	no		261	307
	timber skeleton	yes	420	185	235
	tiled wall			426	480
	tiles	no			
	grout	no			
ceiling cover					
	plasterboard	no		546	641
floor finish					
	tiled flor	no		1420	1601
	tiles				
	grout				
	TOTAL		1148	92402	101750
	STRUCTURE		50	86469	96215
	SKIN		679	2431	1491
	SPACE		420	3502	4044

Figure 5.6: Excel spreadsheet Part 5/5, end-of-life stage House A.

5.1.3 Step 3 - initial scenario

The Material Flow Analysis has different layout than the calculations in the Excel sheet. The MFA structure is based on following the flows from off-site production, to on-site construction, the stock, waste and division of waste into the categories reused, recycled and landfill. The previous calculations follows the General information, Construction stage, Usage stage and End of life which describes the flows during three different time-based periods. The MFA is set for a specific time frame, and when describing all three stages at ones, it will combine material flows from different stages depending on the actions. Figure 5.7 visualises the flows of materials based on processes instead of stages. The processes are off-site production, on-site construction and stock, with waste generation for all 3 of them. The total results are summarised for each stage, each layer and each waste category. Figure 5.7 is visualising the MFA structure constructed earlier in 4.2 which is also included here for comparison as figure 5.8.

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	237956
construction stage	215460	8432	207028	12045	194983	211511	reused	1962
usage stage	22497	3917	18580	2052	16528		recycle	115077
total	237956	12349	225608	14097	211511		landfill	120917

STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	196955
construction stage	196955	4350	192606	10189	182416	182416	reused	50
usage stage	0	0	0	0	0		recycle	93241
total	196955	4350	192606	10189	182416		landfill	103665

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	17663
construction stage	8605	3490	5115	514	4601	9656	reused	1283
usage stage	9058	3474	5584	529	5055		recycle	11291
total	17663	6964	10699	1043	9656		landfill	5089

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	23338
construction stage	9900	592	9308	1342	7966	19438	reused	630
usage stage	13439	443	12995	1522	11473		recycle	10544
total	23338	1035	22303	2864	19438		landfill	12164

Figure 5.7: Redistribution of values from the Excel sheet to fit the MFA, initial scenario

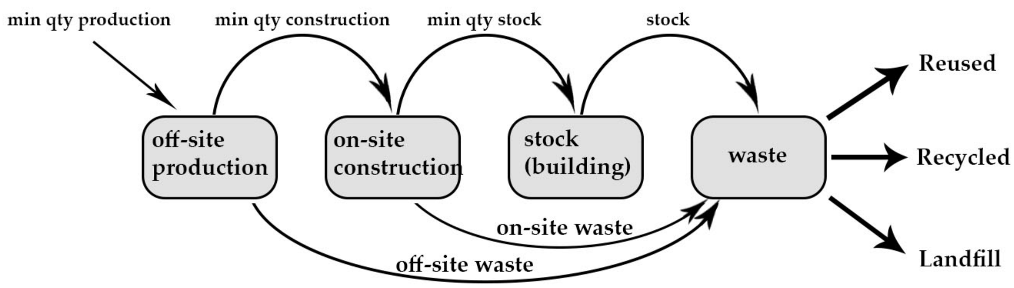


Figure 5.8: Same as figure 4.2, for comparison to the calculated MFA table 5.7

5.2 Alternative 1

Alternative 1 is based on the design principles “Selecting Materials”, “Design for Disassembly” and “Building in Layers” and "Designing-out waste". The reason of merging these principals is because of the major impact and similarity between them in the literature, which as well results in selection of same component. Because of the connection between these design principles, they are selected to structure a scenario together.

5.2.1 Step 4 – Creation of Alternative 1 Scenario

Building in layers implies that the components between the layers are detachable since they have different lifespans, which is also required in the criteria of building for disassembly. To create a building which can be easily disassembled the correct materials and components must be chosen. The conclusions in the theory of selecting materials chapter point out that the elements should be made to be easily disassembled. Finding a way to implement one without the other would be counter-productive from the aspect of creating a scenario which is inspired by circular economy (For example, there is a way to select components and materials to only suit the design principle building in layer but not design for disassembly, by actively not having the possibility for disassemble within the layers. This would probably not give an interesting variation for analysing the material flow).

Straight forward criteria are created to simplify the selection process.New materials and components are selected based on the criteria:

1. Avoid mixing technical and biological materials within the components
2. No connection between layers when assembled to simplify disassemble
3. Long used components should be having a long life and be reusable, components often replaced should be organic or recyclable.

The design choices are majorly inspired by ARUP Circular Building, where design choices are made by a team of professionals and are selected according to principals of circular economy, see chapter 2.2.1. Figure 5.9, 5.10 and 5.11 describe the alternative components one layer at time. The information about refurbishing is taken from Appendix 1.2, Affected components. Only components satisfying all the criteria as well as being available on the market were selected. Comparison between the different components of House A and Alternative 1 and 2 can be seen in figure 5.12.

Structure

Structure is the layer which other layers are excessively dependent on, where components with a longer lifespan should be invested. Main components of the floor structure will be constructed in steel joist and noggin with a hardwood boarded floor panels. Das Click Brick (ClickBrick®,2018) is a detachable cradle to cradle product, a brick which can be assembled without any mortar. The load bearing structure of the roof and the poles are chosen to be of steel as well, since steel is a strong, durable and reusable product (Whirlwindsteel, 2018) . (Assumptions were made that the lightweight steel floor structure weight approximately 50 kg/m2, the exterior wall, 30 kg/m2 and the roof structure 40 kg/m2)(Lightweight Steel Framing, 2002). The flooring of the veranda is covered by Tricoya extreme (MEDITE® TRICOYA®, 2018) - a waterproof long-lasting wood panel which is suitable for flooring as well as being an organic product. The production is non-toxic and sustainable. The car park is produced of a regular concrete slab.

Element	Component	Weight	Replaced	Reusable
Floor structure	Steel structure	7750	0	Yes
	Timber	1163	0	Yes
	Tricoya Extreme	345	0	No
	Concrete slab (carpark)	16200	0	No
Exterior walls	Das Click Brick	19050	0	Yes
	Steel structure	3810	0	Yes
Roof Structure	Steel structure,	12800	0	Yes
	Steel details	250	0	No
Support Poles	Steel Poles	99	0	Yes

Figure 5.9: Layer structure, Alternative 1. The weight refers to the in-situ component without waste.

Skin
Skin is the protective layer of the house, the components must be durable and shielding. The exterior wall covering is assumed to be replaced once during the lifetime of the building due to aesthetics. Tricoya extreme is used in the skin layer as wel, it is a waterproof long-lasting wood panel which is suitable for cladding as well. Since the windows are a reusable component, the decision is made to keep the same windows as in the initial scenario. The roof sheeting is selected to be Envirotile 8Fix (Green Sustainable Products, 2018), durable product created of recycled plastic and is suitable to be recycled again after usage. Envirotile 8Fix can sustain harsh wind loads, which are present in the study area. Hemp insulation (Black Mountain Insulation, 2018) is an organic, bio-degradeble, non-toxic fibre insulation with a Thermal Conductivity of 0.039 W/m°K (Compared to 0.04 for Fibreglass (Engineering ToolBox, 2001).

Element	Component	Weight	Replaced	Reusable
Roof Sheeting	Envirotile	2254	0	No
Windows	Window	1208	1	Yes
Exterior wall covering	Tricoya extreme	1184	1	No
Insulation	Hemp insulation	1230	0	No

Figure 5.10: Layer skin, Alternative 1. The weight refers to the in-situ component without waste.

Space
Space is the layer which need to be adaptable, since the design preferences or purpose of the building might change. Space is the layer most affected by the refurbishment patterns. The refurbishment patters in this layer is mostly short-term compared to buildings life-time. Components often replaced should be organic or recyclable according to criteria 3. Half of the interior walls are assumed to be completely refurbished, with all the components. The outer components of the wall, set to be the wood wool board (Baux aucoustic panels, 2018), is assumed to be changed at least once. The wet areas which will connect to plastic panels are changed at least 2 times. Most components are selected for a shorter lifetime, except the wall steel stud. The wall is made to be disassembled, therefore it is assumed when the room layout is changed, the same steel frame will be used to construct the new wall or be saved for the next renovation project. Therefore the replacement is set to 0 times, the replacement will happen but not create a new material flow, since the metal wall stud is reused within the stage. The panels are not assumed to be reused due to new design preferences and the complexity of detaching components without harming them. The wood wool board is a low-emission, sound absorbing, recyclable product made of wood, water and cement (Baux acoustic panels, 2018) . Wood is to be used in dry areas as flooring. Instead of tiling the wet areas, plastic panels can be used, made of waste products (Haghighat F, 2009).

Element	Component	Weight	Replaced	Reusable
Interior Walls	Steel stud	1989	0*	Yes
	Wood wool board,	1140	1	No
	Tricoya Extreme	266	1	No
	Plastic panels (wet)	130	2	No
Floor	Wood	1000	1	Yes
	Plastic panels (wet)	72	2	No
Ceiling cover	Wood wool	2419	0.5	No

Figure 5.11: Layer space, Alternative 1. The weight refers to the in-situ component without waste. The steel stud is given the value zero, since it is assumed that the steel skeleton will be replaced within the building to create new walls

5.2.2 Step 1, 2, 3 – Alternative 1

The excel of database collection is set up by the same method as in the initial scenario with new components and the values related to them, see Appendix A1, figure A1. General information is found for the new components, to calculate the masses.

Charactarisation of stages - the calculations are proceeded for the construction stage, the usage strange and the end of life in the same manner as for House A, see Appendix A1, figure A2. Calculations for number of replacement during 70 years are proceeded for the new components, with new life expectancy but same refurbishment patterns due to aesthetics, see figure 5.12 and Appendix A1, figure A3 . End-of-life calculations can be seen in Appendix A1, figure A2.

	INITIAL SC.			ALT. 1		
Element	***Component***	***Number of Replaced***	***Reusable***	***Component***	***Replaced during 70 years***	***Reusable***
Floor structure	Concrete Reinforcement	0 0	No No	Steel Timber	0 0	Yes Yes
Exterior wall	Concrete blocks Reinforcement Concrete filling	0 0 0	No No No	Das Click Brick Steel structure	0 0	Yes Yes
Roof structure	Timber structure Steel details	0 0	Yes No	Steel Steel details	0 0	Yes No
Support poles	Steel	0	Yes	Steel	0	Yes
Roof Sheeting	Colourbond steel sheeting	1	No	Envirotile	0	No
Windows	Windows	1	Yes	Windows	1	Yes
Exterior finish	Fibrecement Render	1 2	No No	Tricoya extreme	1	No No
Insulation	Fibreglass	0	Yes	Hemp insulation	0	No
Interior walls	Plasterboard Fibrecement Timber skeleton Tiles Grout	1 1 1 2 2	No No Yes No No	Wood Wool Tricoya Extreme Steel Structure Plastic panels	1 1 0 2	No No Yes No
Floor	Tiles Grout	2 2	No No	Wood Plastic panel (wet)	0 2	Yes No
Ceiling	Plasterboard	1	No	Wood Wool	0.5	No

Figure 5.12: Comparison of components, number of replacement and reuse between Initial scenario and Alternative 1

Step 3 - The calculations and the preparation for the MFA and the Sankey Diagrams are proceeded in the same measure as for House A, see figure 5.13.

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	106077
construction stage	94829	15914	78915	4257	74657	81068	reused	25538
usage stage	11248	3474	7774	1363	6411		recycle	48459
total	106077	19388	86689	5620	81068		landfill	32078

STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	75365
construction stage	75365	11410	63955	2489	61466	61466	reused	22336
usage stage	0	0	0	0	0		recycle	32944
total	75365	11410	63955	2489	61466		landfill	20085

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	15294
construction stage	9627	3044	6583	407	6176	8567	reused	1208
usage stage	5667	2880	2787	395	2392		recycle	8737
total	15294	5925	9369	802	8567		landfill	5350

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	15418
construction stage	9837	1460	8377	1361	7016	11035	reused	1995
usage stage	5581	593	4987	968	4019		recycle	6778
total	15418	2053	13365	2329	11035		landfill	6643

Figure 5.13: Redistribution of values from the excel database to fit the MFA, Alternative 1

5.3 Alternative 2

According to the design principals, retaining existing structures is the most effective strategy of circular economy, which is the main focus of Alternative 2. This scenario has the same components as Alternative 1, but the lifetime is prolonged to 140 years.

5.3.1 Step 4 – Creation of Alternative 2 Scenario

This scenario will evaluate the strategy of designing for adaptability, retaining existing buildings. Calculating material consumption of a prolonged lifetime will indicate the value of prolonging the lifetime in the comparative unit kg. The components of Alternative 1 are selected for the analysis. Designing for adaptability is close to other important criteria from the other design methods mentioned in the theory chapter. Designing for disassemble and Building in Layers is important for adaptability, since this creates flexibility which enables a building to adapt for new purposes. Selecting materials is influencing as well, the selection should follow the principal of circular economy and separate the biological and technical material. New components will not be selected, they are already chosen according to circular economy principals. This scenario has prolonged lifetime and components selected according to circular economy principals, which means it meets all the circular economy design strategies: Building in layers, Designing-out waste, Design for adaptability, Design for disassembly and Selecting Materials, see figure 2.1 Theory chapter.

5.3.2 Step 1, 2, 3 - Alternative 2

Same components are used for the database collection for Alternative 2 as for Alternative 1, no new database collection is required, see Appendix A1, figure A5 for excel database sheet. The construction stage is also proceeded in the same manner as in Alternative 1, see Appendix A1, figure A6. The usage stage differs from Alternative 1, since the lifetime is prolonged to 140 years. More of the components will reach the end of life and a new usage pattern is constructed based on lifetime and refurbishment pattern, see the table 4.13. Flexibility is key to a buildings survival while building will face more refurbishments Cheshire D, 2016 [**?**]. The usage stage with the new number of replacements can be seen in Appendix A1, figure A7. The end-of-life is calculated in same manner but with updated information, see Appendix A1, figure A8.

Element	Component	Life expectancy	Refurbishment during 140 years	Reusable
Floor structure	Steel structure Timber Tricoya extreme Concrete slab (parking)	250 150 70 100	0 0 1 1	Yes Yes No No
Exterior wall	Das Click brick Steel structure	200 250	0 0	Yes Yes
Roof structure	Steel structure Steel details	200	0	Yes No
Support poles	Steel	150	0	Yes
Roof Sheeting	Envirotile (plastic panels)	70	1	No
Protection	Hemp insulation	140	0	
Windows	Windows (aluminium and glass)	44	3	Yes, as element
Exterior wall covering	Tricoya extreme (wood panels)	70	2	No
Insulation	Hemp insulation	140	0	No
Interior walls	Steel frame, Wood wool board, Tricoya extreme Plastic panels (wet areas)	250 70 70 70	0* 4 4 4	Yes No Yes No
Floor	Wood Plastic panels (wet areas)	100 70	2 4	Yes No
Ceiling	Wood wool	70	2	No

Figure 5.14: Number of replacements during 140 years and possibility to reuse the product for Alternative 2

Step 3 - The preparation of data from the excel sheets to the MFA is completed by same method as previously, see figure 5.15. The difference is the time frame, which is only noticeable in the MFA in the increased consumed material values. The processes are the same and time is not represented. The value can be described as kgs consumed during one lifetime.

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	149176
construction stage	94829	15914	78915	4257	74657	113362	reused	27246
usage stage	54347	10090	44257	5553	38704		recycle	69925
total	149176	26004	123172	9810	113362		landfill	52003

STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	93519
construction stage	75365	11410	63955	2489	61466	78355	reused	22336
usage stage	18153	182	17972	1082	16889.5		recycle	41449
total	93519	11592	81927	3571	78355		landfill	29734

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	27612
construction stage	9627	3044	6583	407	6176	14720	reused	2415
usage stage	17985	8651	9335	790	8545		recycle	16164
total	27612	11695	15917	1197	14720		landfill	9033

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	28045
construction stage	9837	1460	8377	1361	7016	20286	reused	2495
usage stage	18208	1257	16951	3681	13270		recycle	12312
total	28045	2717	25328	5042	20286		landfill	13236

Figure 5.15: Redistribution of values from the Excel sheet to fit the MFA, Alternative 2, values for 140 years life-span

6

Discussion

6.1 Sankey diagrams

Sankey diagrams are visualising the material flows within the system. Materials flow from Production, to Construction and Stock, creating waste during each process. When the house has reached end-of-life, the stock becomes an outflow to the waste category, divided into reuse, recycling and landfill. Recycling category includes the downcycling and incarnation, since the exact values are unknown. Initial scenario of house A requires an inflow of 257 tonnes of material to create the stock of 211 tonnes, see figure 6.1. 119 tonnes of material is circulated back into the system. The outflow of waste during production stage is 12.3 tonnes, while on-site production is 14 tonnes.

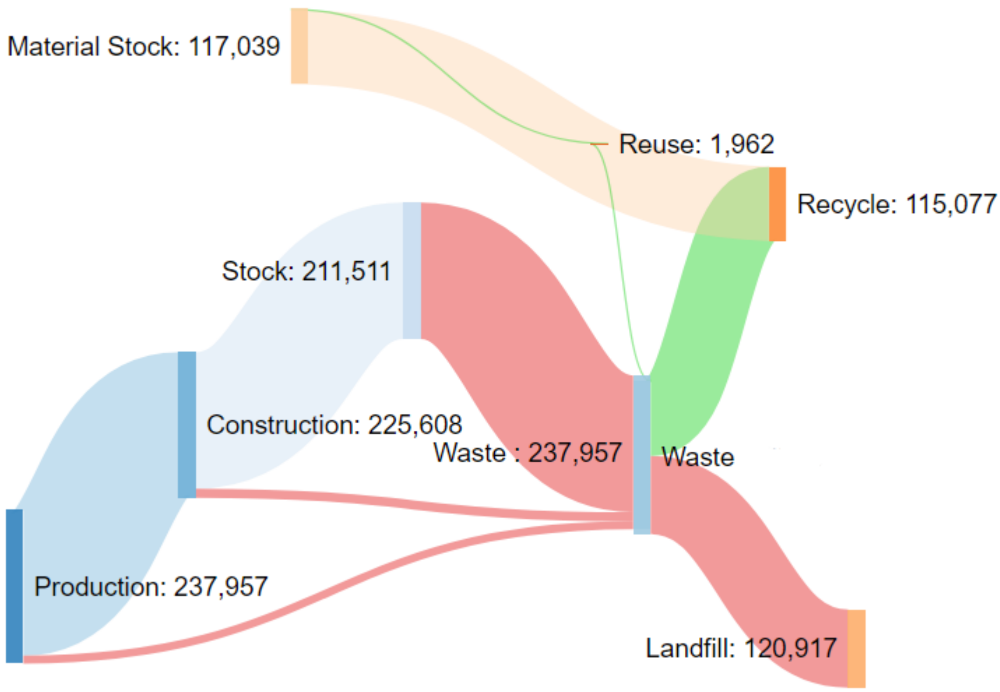


Figure 6.1: Sankey diagram Initial scenario

Alternative 1 requires 106 tonnes of material inflow to create a stock of 81 tonnes, see figure 6.2. 74 tonnes are circulated back into the system while 32 tonnes outflows to landfill. The production waste outflow is 19.4 tonnes while the on-site production is 5.6 tonnes.

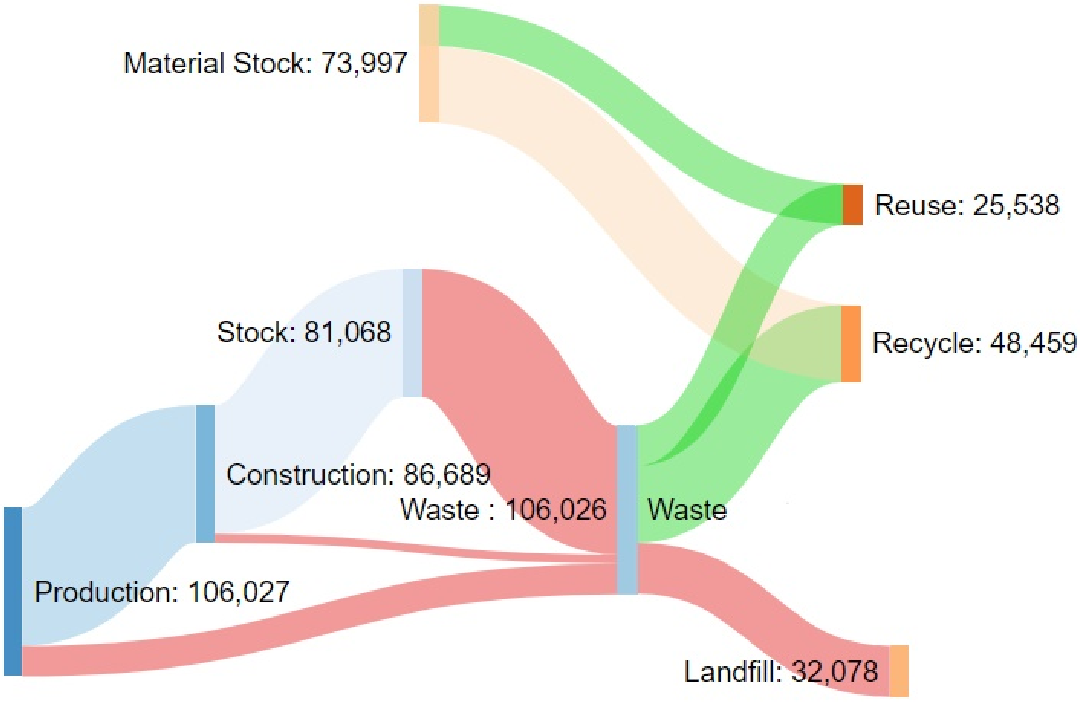


Figure 6.2: Sankey diagram Alternative 1

To be comparable, the results of the Alternative 2 are halved (to present the flows for the set time of 70 years, instead of 140 years). Alternative 2 requires 75 tonnes of material to create a stock of 57 tonnes, see figure 6.3. 26 tonnes of the used materials ends up in landfill while 40 tonnes circulates back. The outflow of production waste is 26 tonnes, while construction waste outflow is 9.8 tonnes.

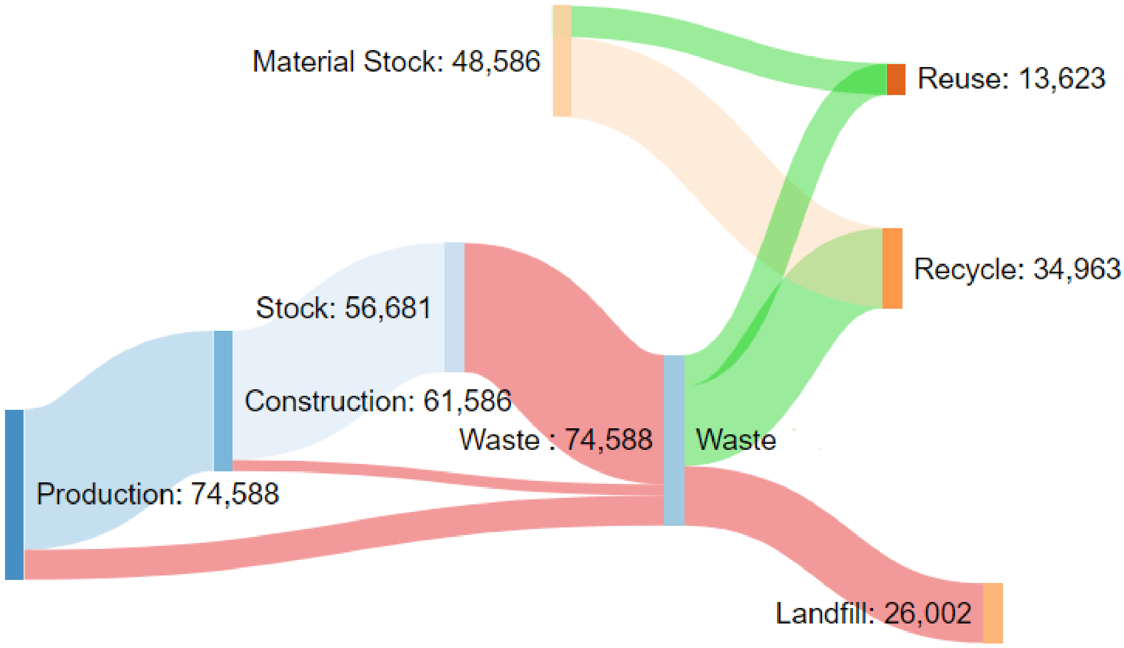


Figure 6.3: Sankey diagram Alternative 2

6.2 Ratio of circularity

The following results present the circularity within the different scenarios according to the formula:

$$\text{CE ratio of scenario} = \frac{(Recycled[\mathbf{kg}] + Reused[\mathbf{kg}]) \times years}{Total[\mathbf{kg}] \times years}$$

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	237956
construction stage	215460	8432	207028	12045	194983	211511	reused	1962
usage stage	22497	3917	18580	2052	16528		recycle	115077
total	237956	12349	225608	14097	211511		landfill	120917

Figure 6.4: The material flows of the Initial scenario scenario during 70 years. CE ratio of the Initial scenario is 0.49

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	106077
construction stage	94829	15914	78915	4257	74657	81068	reused	25538
usage stage	11248	3474	7774	1363	6411		recycle	48459
total	106077	19388	86689	5620	81068		landfill	32078

Figure 6.5: The flows within Alternative 1 during 70 years. CE ratio of Alternative 1 is 0.70

TOTAL	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	149176
construction stage	94829	15914	78915	4257	74657	113362	reused	27246
usage stage	54347	10090	44257	5553	38704		recycle	69925
total	149176	26004	123172	9810	113362		landfill	52003

Figure 6.6: The flows within Alternative 2 during the timespan of 140 years. CE ratio of Alternative 2 is 0.65

The CE ratio of Initial scenario and Alternative 1 differ by 20% but when comparing the requirement for masses for production, as well as material ending up in landfill, the performance of alt1 is even more outstanding.While The Initial SCenario generates 120 tonnes of landfill during its lifetime of 70 years, Alternative 1 generates 32 tonnes. That is just above one fourth of weights difference. Alternative 2 decreases the masses ending up in landfill even more, 26 tonnes is 21,6% of the landfill masses. Initial scenario requires 238 tonnes of material inflow to the production process to generate the desired stock for service of 70 years. Same benefit (volume of house creating living space for people) could be acquired by 106 tonnes using Alternative 1 or 74,5 tonnes of material using Alternative 2. A decrease of 69% in processed masses is possible by implementing the design principals of circular economy.

Another comparison is to analyse the processed material per year, by using the calculation (Processed material/lifetime of building):

The initial scenario requires 3399 kg/year, Alternative 1 1515 kg per year and Alternative 2 1066 kg/year.

The amount of on-site versus off-site waste is changed, while being slightly higher onsite during the initial Initial scenario scenario, the dominant waste flow comes from the production stage for Alternative 1 and Alternative 2. This is directly related to the choice of components, where the pre-fab are more desired according to circular economy strategies, Zimmann et. al 2016.. Elimination of waste from construction is desired to decrease land use, decrease transportation costs and improve waste handling. Pre-fabricated components were prioritised.

The formula CE ratio of scenario is simplifying the outcome by equalizing the value of reuse with recycling. Downcycling and recovery for energy are included in the category recycling, which is not as desired as reuse, since it decreases the value of the material as well as craves more energy and transportation. The figure 2.1 in the chapter design strategies defines the hierarchy, which starting with the most favourable is: retain, refit, refurbish, reclaim, reuse, remanufacture, recycle/compost. The rates for the division between the landfill and recycling/recover are obtained for the case study area, but the division between recycling, downcycling and recovering is uncertain. Proportions for recycling, downcycling and incineration are therefore assumed to be similar as for following example from UK, SteelConstruction, 2013 [?] The recycling, reuse, downcycling, recovering and landfill rates are visualised for the three categories timber, steel and concrete. When combining the values for incineration and downcycling, and creating a mean between concrete, timber and steel, a mean value of 44.6% of downcycling/recovering is obtained. The cathegory recyled which consists recycled, recovered and downcycled, is therefor assumed to be 44.6% recovered and downcycled, and 55.4% recycled.

It is complicated to estimate how the difference in worth should be valued for downgrading of components, when applied to the CE formula. Reuse is worth more than recycling, which is worth more than downcycling/recovery. But all these actions are more desired than landfill, which is valued as zero. An estimation is set to a grading scale of 100% worth for reusage, 66% worth for recycling and 33% worth for downcycling, multiplied by the mass of component. The grading scale is selected to be equally differing steps by 1/3 in total, creating an assumption since evaluation would be too uncertain. Each of the components would have a different value of how much less desired a downgrading is than a reuse.

$$\text{Modified CE ratio} = \frac{(1(Recycled[\mathbf{kg}]) + 2/3(Reused[\mathbf{kg}]) + 1/3(Downcycled[\mathbf{kg}])) \times years}{Total[\mathbf{kg}] \times years}$$

Circularity values if an approximate value of that 44,6% of all recycled waste is downcycled/recovered, and a new value system, where reused is 100% worth of the mass, recycled would be worth 2/3rds and downcycling/recovering is worth 1/3rd.

	Initial scenario	Alternative 1	Alternative 2
Reused	1962	25538	27246
Recycled	51324 *(2/3) =34216	26847*(2/3) =17898	38739*(2/3) =25826
Downgraded and recovered (incineration)	63753 * (1/3) =21251	21612*(1/3) =7204	31186*(1/3) =10395
The modified CE ratio	24%	48%	46%

Figure 6.7: Circularity values with modified CE ratio

6.3 Comparison between layers

The layers of the different scenarios differ by components and volumes. Circularity of each layer and scenario is calculated by the formula

$$\text{CE ratio of scenario} = \frac{(Recycled[\mathbf{kg}] + Reused[\mathbf{kg}]) \times years}{Total[\mathbf{kg}] \times years}$$

CE ratio of Initial scenario layers, see figure 6.8:
Structure – 47%, Skin – 71%, Space – 48%. The inflow to the production is set to 197 tonnes for the structure layer, 17.6 tonnes for the layer skin and 23 tonnes for the layer space. Most waste is created during the on-site construction of the structural layer – 10 tonnes, following by almost 7 tonnes created for the off-site production for the skin layer, which is approximately 40% waste rate. The main reason is the highly material demanding aluminium production – to create 1 kg of aluminium 4 kg of bauxite must be processed, The Aluminium Assosiation, USA, 2018. If recycled aluminium is to be used, the waste rate would decrease.

STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	196955
construction stage	196955	4350	192606	10189	182416	182416	reused	50
usage stage	0	0	0	0	0		recycle	93241
total	196955	4350	192606	10189	182416		landfill	103665

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	17663
construction stage	8605	3490	5115	514	4601	9656	reused	1283
usage stage	9058	3474	5584	529	5055		recycle	11291
total	17663	6964	10699	1043	9656		landfill	5089

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	23338
construction stage	9900	592	9308	1342	7966	19438	reused	630
usage stage	13439	443	12995	1522	11473		recycle	10544
total	23338	1035	22303	2864	19438		landfill	12164

Figure 6.8: Flows within Initial scenario, divided by Layers

CE ration of Alternative 1 layers, see figure 6.9:
Structure – 73%, Skin – 65%, Space – 57%. In this scenario, the greatest waste rate is coming from the off-site production of the Structure layer, influenced by the material demanding steel production process.

STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	75365
construction stage	75365	11410	63955	2489	61466	61466	reused	22336
usage stage	0	0	0	0	0		recycle	32944
total	75365	11410	63955	2489	61466		landfill	20085

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	15294
construction stage	9627	3044	6583	407	6176	8567	reused	1208
usage stage	5667	2880	2787	395	2392		recycle	8737
total	15294	5925	9369	802	8567		landfill	5350

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	15418
construction stage	9837	1460	8377	1361	7016	11035	reused	1995
usage stage	5581	593	4987	968	4019		recycle	6778
total	15418	2053	13365	2329	11035		landfill	6643

Figure 6.9: Flows within Alternative 1, divided by Layers

CE ration of Alternative 2 layers, see figure 6.10:
Structure – 68%, Skin – 67%, Space – 53%. In this prolonged version of scenario 1, the refurbishment waste is increasing the flows and almost equalises the waste generation between off-site production of layer structure and off-site production of layer skin influenced by the aluminium production of window frames.

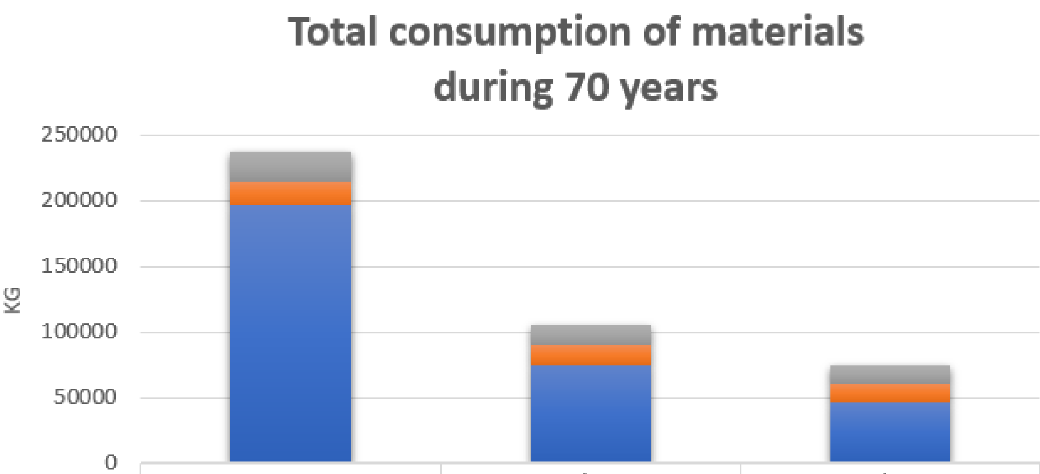
STRUCTURE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	93519
construction stage	75365	11410	63955	2489	61466	78355	reused	22336
usage stage	18153	182	17972	1082	16889.5		recycle	41449
total	93519	11592	81927	3571	78355		landfill	29734

SKIN	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	27612
construction stage	9627	3044	6583	407	6176	14720	reused	2415
usage stage	17985	8651	9335	790	8545		recycle	16164
total	27612	11695	15917	1197	14720		landfill	9033

SPACE	off-site production	off site waste	on site construction	on-site waste	stock	end of life (stock waste)	total waste	28045
construction stage	9837	1460	8377	1361	7016	20286	reused	2495
usage stage	18208	1257	16951	3681	13270		recycle	12312
total	28045	2717	25328	5042	20286		landfill	13236

Figure 6.10: Flows within Alternative 2, divided by Layers

Compared to the CE ratio of the total scenarios, it can be noticed that the layer structure has been the most influential due to its magnitude. Structure is the layer with the greatest mass within all 3 of the scenarios, see figure 6.11.



	House A	Alt 1	Alt 2
Space	23338	15418	14023
Skin	17633	15294	13806
Structure	196955	75365	46760

Figure 6.11: The total consumption during a span of 70 years, visualising the different scenarios and the masses of the layers

Due to the great impact on the results, the layer structure is analysed more in detailed. The structure is clearly the heaviest layer within all 3 scenarios, while space and skin are approximately equal. Being the heaviest of layers makes the structure most influential during the Material Flow Analysis. The major decrease of mass occurred within the structure layer, where the main difference was decrease of masonry components to only the carparking and substituting everything else with lightweight steel. The advantage of steel is not only decrease in total mass, but also the great potential to be reused or recycled. If a different finish than the masonry product Click-Brick would have been used, the weight could have been decreased even more, but an assumption was made that light weight steel and cladding would not have lived up to the wind standards in study the area.

While not including a construction investigation, the ambition is to create realistic alternative for the case study area. Comparing the masonry and steel products, concrete has the advantage of being less energy demanding to produce. This is not influencing the Material Flow Analysis, but an important fact to point out, since this has an environmental impact.

A basic comparison is created between the energy demand to create the steel and the concrete products within the layers of Structure. Steel requires approximately 25 MJ per 100 kg steel, Rankin J.2012 , while 2400 kg of concrete requires 2,775 MJ, Guidetti F. 2018.

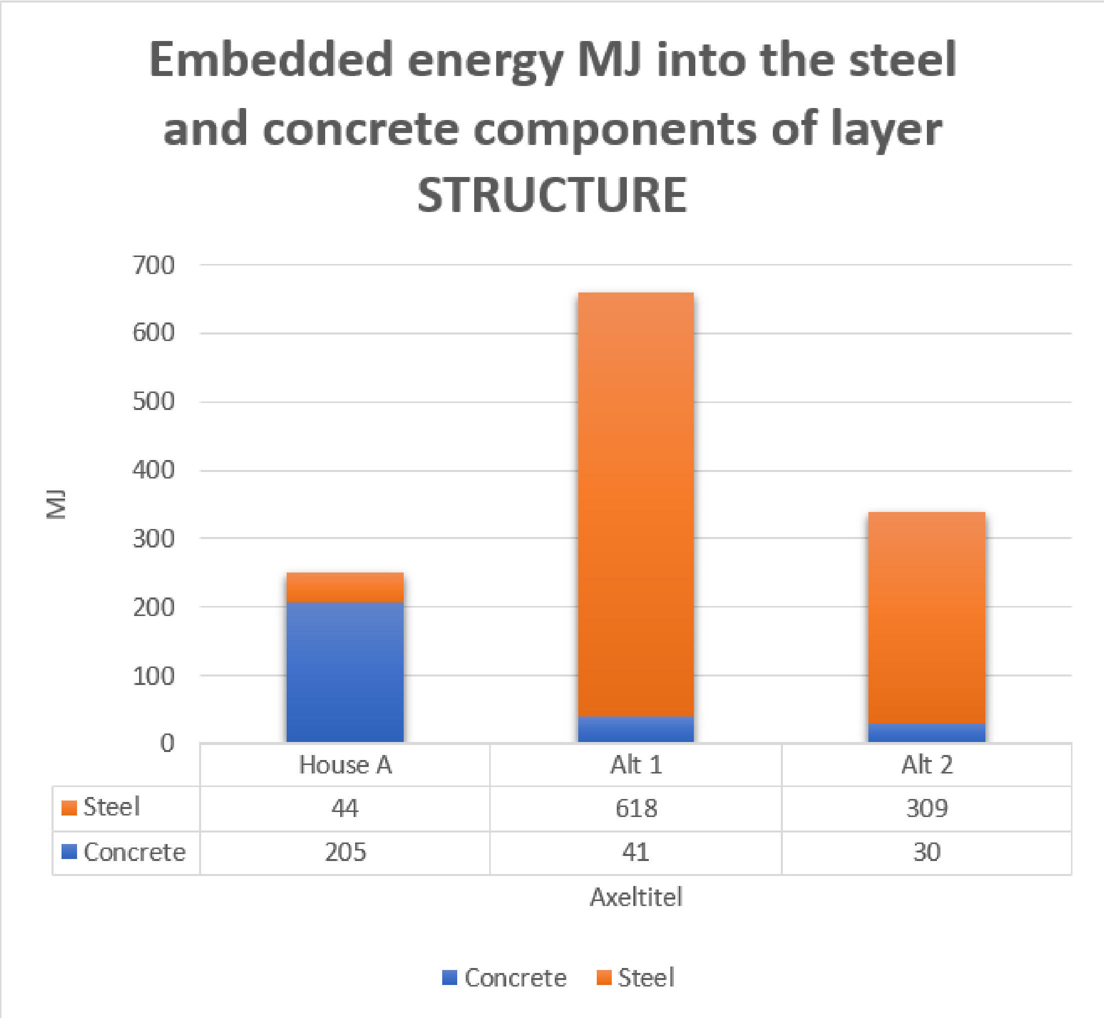


Figure 6.12: Energy consumption embedded in the steel and concrete components within the layer structure, set for 70 years

The steel and concrete components within the structure layer of Initial scenario demands 249 MJ of energy, while for Alternative 1, the amount of energy adds up to 659 MJ (an increase by 164%). If alternative 2 is applied instead, the energy demand is set to 339 MJ during the span of 70 years, which is an increase of 36% from scenario Initial scenario. Although steel production is more energy demanding, the reduction in weight decreases the energy used for transportation purposes. Different energy demand standards exist for different components. An tonnes of steel is set to require 0.08 MJ/km for transportation, while concrete requires 0.1 MJ/tonnes/km, Miller A 2018.

The in-situ material consumption for Initial scenario is compared to Alternative 2 (140 years not altered for MFA), being the two most diverse options.

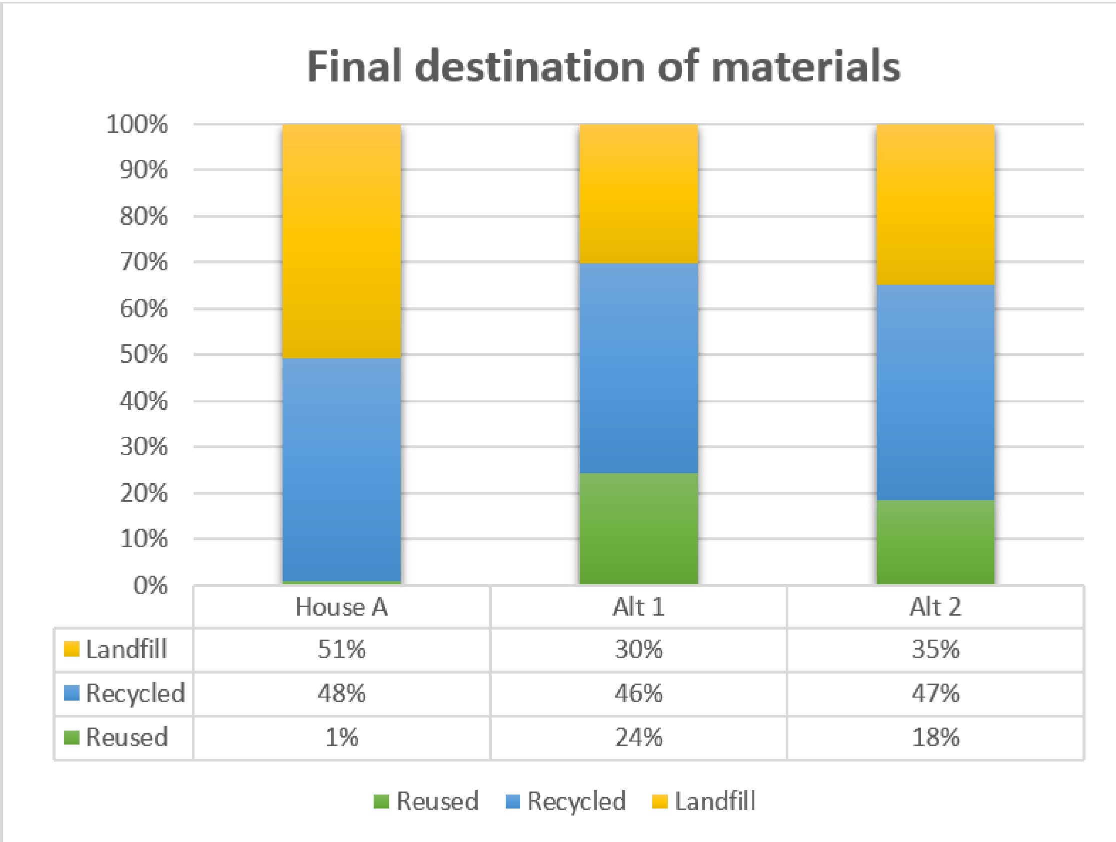
Steel Alt 2: 24.7 * 0.08 MJ/km
Steel Initial: 1.78 * 0.08 MJ/km
Concrete Alt 2: 32.4 * 0.1 MJ/km
Concrete Initial: 177 * 0.1 MJ/km

Tot transportation energy consumption for steel and concrete transportation Alternative 2 compared to Initial scenario:

Initial = 0.1424 + 17.7 = 18.84 MJ/km
Alt 2 = 1.976 + 3.24 = 5.216 MJ/km

Comparison of end destination of waste

Alternative 1 has the best circularity ratio, 70%. The reason why Alternative 2 came second can be explained by that space layer is greater in mass in the Alternative 2, since more components are refurbished there during the longer lifespan. The space layer components are not as often reusable, since many of them were chosen to be biodegradable, due to the shorter life-span and frequent refurbishments.



	House A	Alt 1	Alt 2
Landfill	51%	30%	35%
Recycled	48%	46%	47%
Reused	1%	24%	18%

Figure 6.13: Final destination of waste based on the total outcome of the scenarios, divided between landfill, recycling and reused. Incarnation and downcycling is included in the cathegory recycled

7

Conclusion

The results measure a possibility to improve the CE ratio of the case study building by a total of 21% by selecting different components chosen by design strategy of circular economy. The circularity ratio decreased slightly in the Alternative 2, due to the increased influence of the layer space, with less reusable or recyclable components.

Structure is the most influential layer due to its mass when analysed by MFA since the comparative unit is set to KG. The major influence of the structure layer decreases when the lifetime of the building is prolonged – the mass of the other layers increases since they have more replacement of components and therefore gain total consumed mass over the total lifetime. The result is sensitive to the assumption of the mass of the lightweight steel flame.

There is great potential to decrease the total material mass used to construct a building with the same layout – House A required 238 tonnes of material to the production stage, Alternative 1 decreases the material mass by 55.5% (106 tonnes)and Alternative 2 by 68.5%(75 tonnes, when set for 70 years) – this is something which isn't included in the CE formula but is very important for circular economy.

Major factor decreasing the weight was changing the concrete reinforced wall into lightweight steel. Lightweight steel is more energy demanding than concrete to produce, which is a factor affecting the sustainability aspects as well as the cost of the product. Creating a lighter building structure decreases transportation, which affects the CO_2 impact and the financial aspect.

Material Flow Analysis is unusual to be applied on a one building layer, but can create important information to in a further stage be used on a bigger scale. A building could be designed specifically for a national/regional material flows and tested before mass-production. This would give an estimation of flows to be created as a consequence of mass production and give an opportunity to prepare a good waste management plan.

Some of the values were difficult to estimate, for example weather to choose the waste rate of primary aluminum production or the recyced aluminium productions waste rate. During the initial case study, it was understood that the cheapest price would win the tendering process, and the cheapest windows while having a sufficient standard would be chosen. There was no room for investigation of the sustainability of the product in that kind of business process.

Uncertainties are related to building practices as well. Only estimations can be made about how much waste is produced on-site since the human factor plays in. Cutting of plasterboard was one of the more excessive waste rates, which was set to 25%. Some statistics expected a waste rate between 10-20% source while other investigations resulted in a waste rate between 30-50% due to bad off-cutting practice and over-delivery source. Overall assumptions had to be set to create a bigger picture of the waste flows.

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A

Appendix 1

A.0.1 Refurbishment statistics summary

The top five reasons for renovation are:
1. Improving design/look and feel
2. Improving functionality
3. Increasing resale value
4. Improving energy efficiency
5. Minimizing costs.

The top five inside renovation projects are:
1. Living/family room
2. Kitchen
3. Guest bedroom
4. Master bathroom
5. Master bedroom

The top five exterior upgrades are:
1. Exterior paint
2. Veranda
3. gutters/downpipes
4. exterior doors
5. windows/skylights

A.1 Excel

Element	Component									
Structure		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site p	Life exp. years	Recycling
Floor structure										
	Steel structure		155	50 kg/m2	7750	yes	0	0.3	250	0.82
	Timber/Particle board		155	7.5 kg/m2	1163	yes	0.07	0.34	150	0.44
	tricoya extreme		35	9.85 kg/m2	345	no	0.25	0.01	70	0.44
	garage slab concrete		45	2400	16200	no	0.05	0.01	100	0.47
Exterior wall			127							
	Das Click Brick				19050	yes	0.07	0	200	0.47
	Steel frame			30 kg/m2	3810	yes	0	0.3	250	0.82
Roof structure			320							
	Steel			40 kg/m2	12800	yes	0	0.3	200	0.82
	Steel details			0.78kg/m2 (battens)	250	no	0	0.3	70	0.82
Poles										
	Steel	0.01			99	yes	0	0.3	150	0.82
Skin		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site p	Life exp. years	Recycling
Roof sheeting			304							
	Envirotile			8.4 kg/m2	2554	no	0	0.01	70	0.46
Windows										
	Windows		24	1m2 = 50.7 kg		yes			44	
	Glass		20	14.96/m2	304		0	0.01		0.34
	Aluminium		7	2800	904		0	0.76		0.82
Wall exterior covering										
	Tricoya Extreme	1.692	141	700kg/m3	1184	no	0.25	0.01	70	0.44
Insulation										
	Hempsulation	41	410	30 kg/m3	1230	no	0.01	0.1	70	0.44
Space		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site p	Life exp. years	Recycling
Interior walls										
	Wood wool board	2.68	143		1140	no	0.25	0.01	70	0.46
	Tricoya Extreme	0.38	27	700 kg/m3	266	no	0.25	0.01	70	0.44
	Steel frame		102	19.5 kg/m2	1989	yes		0.3	250	0.82
	Plastic panel	0.11	36	1200 kg/m3	130	no	0.05	0.01	70	0.46
Ceiling cover										
	Wood wool board		302.4		2419	no	0.25	0.01	70	0.46
Floor finish										
	Timber		100	1000kg/m3	1000	yes	0.07	0.34	150	0.44
	Plastic panel	0.06	20	1200 kg/m3	72	no	0.05	0.01	70	0.46
	TOTAL				74657					
	STRUCTURE				61466					
	SKIN				6176					
	SPACE				7016					

Figure A.1: Alternative 1, Excel sheet 1, general information

Element	Component							
Structure		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Floor structure								
	Steel structure	7750	0	11071	3321	3321	2724	598
	Timber/Particle board	1250	88	1894	644	731	322	410
	tricoya extreme	460	115	464	5	120	53	67
	garage slab concrete	17053	853	17225	172	1025	482	543
Exterior wall								
	Das Click Brick	20484	1434	20484	0	1434	674	760
	Steel frame	3810	0	5443	1633	1633	1339	294
Roof structure								
	Steel	12800	0	18286	5486	5486	4498	987
	Steel details	250	0	357	107	107	88	19
Poles								
	Steel	99	0	141	42	42	35	8
Skin		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Roof sheeting								
	Envirotile	2554	0	2579	26	26	12	14
Windows								
	Windows							
	Glass	304	0	307	3	3	1	2
	Aluminium	904	0	3765	2861	2861	2346	515
Wall exterior covering								
	Tricoya Extreme	1579	395	1595	16	411	181	230
Insulation								
	Hempsulation	1242	12	1380	138	150	66	84
Space		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Interior walls								
	Wood wool board	1520	380	1536	15	395	182	214
	Tricoya Extreme	355	89	358	4	92	41	52
	Steel frame	1989	0	2841	852	852	699	153
	Plastic panel	136	7	138	1	8	4	4
Ceiling cover								
	Wood wool board	3226	806	3258	33	839	386	453
Floor finish								
	Timber	1075	75	1629	554	629	277	352
	Plastic panel	76	4	77	1	5	2	2
	TOTAL	78915	4257	94829	15914	20172	14408	5762
	STRUCTURE	63955	2489	75365	11410	13899	10213	3686
	SKIN	6583	407	9627	3044	3451	2606	845
	SPACE	8377	1361	9837	1460	2821	1588	1231

Figure A.2: Alternative 1, Excel sheet 2, construction stage

Element	Component												
Structure		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Floor structure								waste + component					
	Steel structure	0	0	0	0	0	0	0	no				
	Timber/Particle board	0	0	0	0	0	0	0	no				
	tricoya extreme	0	0	0	0	0	0	0	no				
	garage slab concrete	0	0	0	0	0	0	0	no				
Exterior wall								0					
	Das Click Brick	0	0	0	0	0	0	0	no				
	Steel frame	0	0	0	0	0	0	0	no				
Roof structure								0					
	Steel	0	0	0	0	0	0	0	no				
	Steel details	0	0	0	0	0	0	0	no				
Poles								0					
	Steel	0	0	0	0	0	0	0	no				
Skin		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Roof sheeting													
	Envirotile	0	0	0	0	0	0	0	no				
Windows													
	Windows								yes				
	Glass	1	307	3	304	0	304	307		152	155	53	102
	Aluminium	1	3765	2861	904	0	904	3765		452	3313	2717	596
Wall exterior covering													
	Tricoya Extreme	1	1595	16	1579	395	1184	1595	no		1595	702	893
Insulation													
	Hempsulation	0	0	0	0	0	0	0	no			0	0
Space		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Interior walls													
	Wood wool board	1	1536	15	1520	380	1140	1536	no		1536	706	829
	Tricoya Extreme	1	358	4	355	89	266	358	no		358	158	201
	Steel frame	0	0	0	0	0	0	0	yes*				
	Plastic panel	2	276	3	273	14	259	276	no		276	127	149
Ceiling cover													
	Wood wool board	0.5	1629	16	1613	403	1210	1629	no		1629	749	880
Floor finish													
	Timber	1	1629	554	1075	75	1000	1629	yes	500	1129	497	632
	Plastic panel	2	153	2	152	8	144	153	no	0	153	70	83
	TOTAL		11248	3474	7774	1363	6411	11248		1104	10144	5779	4365
	STRUCTURE		0	0	0	0	0	0		0		0	0
	SKIN		5667	2880	2787	395	2392	5667		604	5063	3471	1592
	SPACE		5581	593	4987	968	4019	5581		500	5081	2307	2773

Figure A.3: Alternative 1, Excel sheet 3, usage stage

Element	Component							
Structure		Component weight	Reused this stage	Reused KG	comp-reused	Recycling rate %	Recycling	Landfill
Floor structure								
	Steel structure	7750	yes	3875	3875	0.82	3178	698
	Timber/Particle board	1163	yes	581	581	0.44	256	326
	tricoya extreme	345	no	0	345	0.44	152	193
	garage slab concrete	16200	no	0	16200	0.47	7614	8586
Exterior wall							0	0
	Das Click Brick	19050	yes	9525	9525	0.47	4477	5048
	Steel frame	3810	yes	1905	1905	0.82	1562	343
Roof structure							0	0
	Steel	12800	yes	6400	6400	0.82	5248	1152
	Steel details	250	no	0	250	0.82	205	45
Poles							0	0
	Steel	99	yes	50	50	0.82	41	9
Skin		Weight KG	Reuseble	Weight reused	comp-reused	Recycling rate %	Recycling	Landfill
Roof sheeting							0	0
	Envirotile	2554	no	0	2554	0.46	1175	1379
Windows							0	0
	Windows		yes	604				
	Glass	304			152	0.34	52	100
	Aluminium	904			452	0.82	370	81
Wall exterior covering							0	0
	Tricoya Extreme	1184	no		1184	0.44	521	663
Insulation							0	0
	Hempsulation	1230	no		1230	0.44	541	689
Space		Weight KG	Reuseble	Weight reused	comp-reused	Recycling rate %	Recycling	Landfill
Interior walls							0	0
	Wood wool board	1140	no		1140	0.46	525	616
	Tricoya Extreme	266	no		266	0.44	117	149
	Steel frame	1989	yes	995	995	0.82	815	179
	Plastic panel	130	no		130	0.46	60	70
Ceiling cover							0	0
	Wood wool board	2419	no		2419	0.46	1113	1306
Floor finish							0	0
	Timber	1000	yes	500	500	0.44	220	280
	Plastic panel	72	no		72	0.46	33	39
	TOTAL	74657		24434	50223	0	28273	21951
	STRUCTURE	61466		22336	39130		22731	16399
	SKIN	6176		604	5572		2659	2913
	SPACE	7016		1495	5522		2883	2639

Figure A.4: Alternative 1, Excel sheet 4, end-of-life

Element	Component									
Structure		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
Floor structure										
	Steel structure		155	50 kg/m2	7750	yes	0	0.3	250	0.82
	Timber/Particle board		155	7.5 kg/m2	1163	yes	0.07	0.34	150	0.44
	tricoya extreme		35	9.85 kg/m2	345	no	0.25	0.01	70	0.44
	garage slab concrete		45	2400	16200	no	0.05	0.01	100	0.47
Exterior wall			127							
	Das Click Brick				19050	yes	0.07	0	200	0.47
	Steel frame			30 kg/m2	3810	yes	0	0.3	250	0.82
Roof structure			320							
	Steel			40 kg/m2	12800	yes	0	0.3	200	0.82
	Steel details			0.78kg/m2 (battens)	250	no	0	0.3	70	0.82
Poles										
	Steel	0.01			99	yes	0	0.3	150	0.82
Skin		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
Roof sheeting			304							
	Envirotile			8.4 kg/m2	2554	no	0	0.01	70	0.46
Windows										
	Windows		24	1m2 = 50.7 kg		yes			44	
	Glass		20	14.96/m2	304		0	0.01		0.34
	Aluminium		7	2800	904		0	0.76		0.82
Wall exterior covering										
	Tricoya Extreme	1.692	141	700kg/m3	1184	no	0.25	0.01	70	0.44
Insulation										
	Hempsulation	41	410	30 kg/m3	1230	no	0.01	0.1	70	0.44
Space		Volume (m3)	Area m2	Density (kg/m3)	Weight KG	Reuseble	Waste raste on-site %	Waste rate off-site prod. %	Life exp. years	Recycling rate %
Interior walls										
	Wood wool board	2.68	143		1140	no	0.25	0.01	70	0.46
	Tricoya Extreme	0.38	27	700 kg/m3	266	no	0.25	0.01	70	0.44
	Steel frame		102	19.5 kg/m2	1989	yes		0.3	250	0.82
	Plastic panel	0.11	36	1200 kg/m3	130	no	0.05	0.01	70	0.46
Ceiling cover										
	Wood wool board		302.4		2419	no	0.25	0.01	70	0.46
Floor finish										
	Timber		100	1000kg/m3	1000	yes	0.07	0.34	150	0.44
	Plastic panel	0.06	20	1200 kg/m3	72	no	0.05	0.01	70	0.46
	TOTAL				74657					
	STRUCTURE				61466					
	SKIN				6176					
	SPACE				7016					

Figure A.5: Alternative 2, Excel sheet 1, general information

Element	Component							
Structure		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Floor structure								
	Steel structure	7750	0	11071	3321	3321	2724	598
	Timber/Particle board	1250	88	1894	644	731	322	410
	tricoya extreme	460	115	464	5	120	53	67
	garage slab concrete	17053	853	17225	172	1025	482	543
Exterior wall								
	Das Click Brick	20484	1434	20484	0	1434	674	760
	Steel frame	3810	0	5443	1633	1633	1339	294
Roof structure								
	Steel	12800	0	18286	5486	5486	4498	987
	Steel details	250	0	357	107	107	88	19
Poles								
	Steel	99	0	141	42	42	35	8
Skin		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Roof sheeting								
	Envirotile	2554	0	2579	26	26	12	14
Windows								
	Windows							
	Glass	304	0	307	3	3	1	2
	Aluminium	904	0	3765	2861	2861	2346	515
Wall exterior covering								
	Tricoya Extreme	1579	395	1595	16	411	181	230
Insulation								
	Hempsulation	1242	12	1380	138	150	66	84
Space		Min qty on-site	Waste on-site	Min qty off-site prod.	Waste off-site prod	Tot waste	Recycled	Landfill
Interior walls								
	Wood wool board	1520	380	1536	15	395	182	214
	Tricoya Extreme	355	89	358	4	92	41	52
	Steel frame	1989	0	2841	852	852	699	153
	Plastic panel	136	7	138	1	8	4	4
Ceiling cover								
	Wood wool board	3226	806	3258	33	839	386	453
Floor finish								
	Timber	1075	75	1629	554	629	277	352
	Plastic panel	76	4	77	1	5	2	2
	TOTAL	78915	4257	94829	15914	20172	14408	5762
	STRUCTURE	63955	2489	75365	11410	13899	10213	3686
	SKIN	6583	407	9627	3044	3451	2606	845
	SPACE	8377	1361	9837	1460	2821	1588	1231

Figure A.6: Alternative 2, Excel sheet 2, construction stage

Element	Component													
Structure		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Floor structure								waste + component					
	Steel structure	0	0	0	0	0	0	0	no		0		
	Timber/Particle board	0	0	0	0	0	0	0	no		0		
	tricoya extreme	2	929	9	919	230	690	929	no		929	409	520
	garage slab concrete	1	17225	172	17053	853	16200	17225	no		17225	8096	9129
Exterior wall													
	Das Click Brick	0	0	0	0	0	0	0	no		0		
	Steel frame	0	0	0	0	0	0	0	no		0		
Roof structure													
	Steel	0	0	0	0	0	0	0	no		0		
	Steel details	0	0	0	0	0	0	0	no		0		
Poles													
	Steel	0	0	0	0	0	0	0	no		0		
Skin		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Roof sheeting													
	Envirotile	1	2579	26	2554	0	2554	2579	no		2579	1187	1393
Windows													
	Windows								yes				
	Glass	3	921	9	912	0	912	921		456	465	158	307
	Aluminium	3	11295	8584	2711	0	2711	11295		1355	9939	8150	1789
Wall exterior covering													
	Tricoya Extreme	2	3190	32	3158	790	2369	3190	no		3190	1404	1787
Insulation													
	Hempsulation	0	0	0	0	0	0	0	no			0	0
Space		Times replaced	Min Qty off-site prod.	Waste off-site prod.	Min qty on-site	Waste on-site	Weight component	Tot. Waste	Reused this stage	Reused KG	Waste minus reused	Recycled	Landfill
Interior walls													
	Wood wool board	4	6143	61	6081	1520	4561	6143	no		6143	2826	3317
	Tricoya Extreme	4	1433	14	1419	355	1064	1433	no		1433	631	802
	Steel frame	0	0	0	0	0	0	0	yes*				
	Plastic panel	4	551	6	546	27	518	551	no		551	254	298
Ceiling cover													
	Wood wool board	2	6516	65	6451	1613	4838	6516	no		6516	2998	3519
Floor finish													
	Timber	2	3258	1108	2151	151	2000	3258	yes	1000	2258	994	1265
	Plastic panel	4	306	3	303	15	288	306	no	0	306	141	165
	TOTAL		54347	10090	44257	5553	38704	54347		2811	51536	27245	24291
	STRUCTURE		18153	182	17972	1082	16889.5	18153		0	18153	8504	9649
	SKIN		17985	8651	9335	790	8545	17985		1811	16174	10899	5276
	SPACE		18208	1257	16951	3681	13270	18208		1000	17208	7842	9366

Figure A.7: Alternative 2, Excel sheet 3, usage stage

Element	Component							
Structure		Component weight	Reused this stage	Reused KG	comp-reused	Recycling rate %	Recycling	Landfill
Floor structure								
	Steel structure	7750	yes	3875	3875	0.82	3178	698
	Timber/Particle board	1163	yes	581	581	0.44	256	326
	tricoya extreme	345	no	0	345	0.44	152	193
	garage slab concrete	16200	no	0	16200	0.47	7614	8586
Exterior wall							0	0
	Das Click Brick	19050	yes	9525	9525	0.47	4477	5048
	Steel frame	3810	yes	1905	1905	0.82	1562	343
Roof structure							0	0
	Steel	12800	yes	6400	6400	0.82	5248	1152
	Steel details	250	no	0	250	0.82	205	45
Poles							0	0
	Steel	99	yes	50	50	0.82	41	9
Skin		Weight KG	Reuseble	Weight reused	comp-reused	Recycling rate %	Recycling	Landfill
Roof sheeting							0	0
	Envirotile	2554	no	0	2554	0.46	1175	1379
Windows							0	0
	Windows		yes	604				
	Glass	304			152	0.34	52	100
	Aluminium	904			452	0.82	370	81
Wall exterior covering							0	0
	Tricoya Extreme	1184	no		1184	0.44	521	663
Insulation							0	0
	Hempsulation	1230	no		1230	0.44	541	689
Space		Weight KG	Reuseble	Weight reused	comp-reused	Recycling rate %	Recycling	Landfill
Interior walls							0	0
	Wood wool board	1140	no		1140	0.46	525	616
	Tricoya Extreme	266	no		266	0.44	117	149
	Steel frame	1989	yes	995	995	0.82	815	179
	Plastic panel	130	no		130	0.46	60	70
Ceiling cover							0	0
	Wood wool board	2419	no		2419	0.46	1113	1306
Floor finish							0	0
	Timber	1000	yes	500	500	0.44	220	280
	Plastic panel	72	no		72	0.46	33	39
	TOTAL	74657		24434	50223	0	28273	21951
	STRUCTURE	61466		22336	39130		22731	16399
	SKIN	6176		604	5572		2659	2913
	SPACE	7016		1495	5522		2883	2639

Figure A.8: Alternative 2, Excel sheet 4, end-of-life

The ReSOLVE framework is a key output of the Ellen MacArthur Foundation's research. It outlines six actions to guide the transition towards a circular economy:

1. Regenerate
2. Share
3. Optimise
4. Loop
5. Virtualise
6. Exchange

1. Regenarate

Regenerating and restoring natural capital - Carefully select the design that minimizes the impact on the ecosystem, by using less quantities, less harmful materials and creating less waste.
Safeguarding, restoring and increasing the resilience of ecosystems - create the building which is adaptable in a sustainable way to the changes it might be facing during its lifetime and afterwards.
Returning valuable biological nutrients safely to the biosphere - create a design which will be able to recover the nutrients back into the origin of the source, returning the value from where it came from instead of using something once and then having it loosing its value.

2. Share

Maximising asset utilisation - create building designs which encourages sharing and flexibility, going outside of the traditional ownership and possession of space.
Pooling the usage of assets - share the innnovative designs, exchange information to create global information assets that everyone can gain knowledge and create change.
Reusing assets - keep the stock of building material in a loop and try to prolong their life by sharing, reselling, avoid of disposal or downgrading

3. Optimize

Optimising system performane - make design choices to avoid lost of value of the materials and components. Reuse and repurpose after end of first usage, avoid downgrading and disposal.
Prolonging an assets life- Ensure that the construction is of high standard, to avoid maintenance cost and resource usage. At the same time, the construction should be flexible for re-purpose. Design the construction for having a long life and flexible usage.
Decreasing resource usage - modular solutions are flexible, creates less waste then on site solutions and are easier to re-use. Start the circular economy approach from

an early stage, by designing and analyzing different designs not only for the construction process and the initial pupose of the building, but the the whole life of the building with different usage scenarios and the demolition process, design for the whole life-cycle from an early stage.
Implementing reverse logistics - create possibilities for the materials and components to have a purpose and be useful after the end of life of the building. Avoid the downgrading of the product (the loss of value, be reused as something less valube, for example when concrete slab is downgraded into pavement material).

4.Loop
Keeping products and materials in cycles, prioritising inner loops. The most effective way to keep a products value is regular maintenance and re usage without altering. If the component has to be recycled and altered, it goes through a bigger loop, it often loses value during the way and consumes energy to be re-purposed. Design for the components to be easy to disassemble and re-purposed as easy as possible. *Remanufacturing and refurbishing products and components* - keeping materials and components in use for longer, decreases the waste and inpact on the environment.There fore, maintain and maximize the usage. *Recycling materials* - when the material or component cannot be in use anymore, it should be recycled, which minimises waste and cuts costs.

5. Virtualize
Displacing resource use with virtual use - if possible, a service enhanced by technology might save money, time and decrease impact on the environment. For example, Netflix replaced real life shops, which saves time, transportation and building materials. *Replacing physical products and services with virtual services* - use different modelling softwares for investigations and prior building to test the product. *Replacing physical with virtual locations* - video conferences saves time and transportation *Delivering services remotely* - use technology to do accurate calculations of materials, avoid oversupply and monitor changes in design.

6. Exchange
Selecting resources and technology wisely - optimize the material extraction, production and construction methods to create long lived products while decreasing waste and enabling re-usage. *Replacing with renewable energy and material sources* - use sustainable energy sources and design an environment which optimizes the energy usage. *Using alternative material inputs* - select materials which can be reused, reduces waste generation and lowers the environmental impacts. *Replacing traditional solutions with advanced technology* - there are many new inventions avalible which can be easier to repair and live longer. *Replacing product-centric delivery models with new service-centric ones* - instead of owning the product, focus on selling the service it is providing. Philips has introduced a service where the customer is buying

the strength and time of the lights instead of the lightbulb itself. That encourages the company to provide long lasting lamps which are easy to re-purpose, since they are responsible for the light after their end of life