Building A Circular Economy

Environmental, financial and technical aspects of reusing building components

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

The construction sector is one of the biggest contributors to global CO_2 emissions and buildings account for a significant part of the energy use in Sweden. Population growth in combination with economic development is putting more pressure on the environment, resulting in escalating consumption trends and larger quantities of raw material extraction. Policies and directives are promoting a circular economy in material flows. Waste avoidance and reuse are priorities in the EU waste hierarchy. Environmental issues are apparent to be a subject of urgency and will conceivably remain problematic for future generations.

Drivers and barriers for implementing a circular model in the Swedish construction industry was studied with interviews, questionnaires and calculations. A fictive house was used as reference point in calculations and survey. In total, 19 interviews and questionnaires were performed. Indicating quality consistency, quality assurance, logistics, timeframes and availability to be the major barriers. Furthermore, the need for a coordinating actor in the reuse process is a reoccurring subject. An additional survey was distributed to all 290 municipalities in Sweden to investigate the flexibility in regulations addressing the poor energy performance in reused windows. The survey results show that using windows with U-values of $2.0\ \mathrm{W/(m^2 \cdot K)}$ is accepted if figures for ”installed effect”, ”average U-value” and ”$\mathrm{EP_{pet}}$” is within the limits regulated in the building codes.

Calculations on LCA and LCC was performed with the purpose of investigating the inbound energy in comparison to energy savings by installing a new ”low energy” window. Results indicate that even windows with bad energy performance are environmentally profitable in many cases when compared to the inbound energy of manufacturing a new high performing window. LCC results indicate that if the windows are to be reused and estimated to last 25 years, the cost involving restauration, transport, dismantling and installation presented in 4.3.2 is financially feasible up to around 70 000 SEK - 100 000 SEK depending on inflation and growth rates.

Concluding from interviews, the feasibility of incorporating circularity to the building sector in Sweden is highly dependent on timeframes. It is apparent that the reuse option must be presented at the earliest of stages, placing focus on contractors and architects. Also, building with the intent of dismantling is seen as a fundamental part of the circular model. Possible drivers are seen as a combination of government tax reductions on reused components and raised taxes on unsorted waste.

Preface

Throughout the thesis we have had the pleasure of meeting knowledgeable and committed individuals in the industry. We would like to give a big thanks to the companies and all the municipalities who participated in interviews and devoted themselves to answering our questions.

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Nomenclature

Downcycling – Reusing a material or component with a new and lower quality of functionality or purpose.

DfD – Designing for Disassembly.

Embodied energy – The sum of all energy required to produce a product.

LCA – Life Cycle Assessment, a calculation of the environmental impact of a product.

Cradle to gate – Assessment of a product from resource extraction until the product leaves the factory.

Cradle to cradle – A full life cycle assessment from resource extraction to usage and recycle phase.

LCC – Life Cycle Cost, a calculation of the total cost for a product during its life cycle.

Virgin materials – Previously unused material.

EEA – European Environment Agency.

EOL – Materials that have reached their end-of-life stage.

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1 Introduction

The construction sector is one of the biggest contributors to the global CO_2 emissions (International Energy Agency, 2017). The energy use of the ”building and building services” sector accounts for approximately 30 % of the total emissions globally and is following an increasing trend (Ekonomifakta, 2017). In Sweden, this segment represents approximately 40 % of the total energy use (Swedish Environmental Protection Agency, 2017).

The rate of which nature revives resources is far below our current frequency of extraction, leading towards resource deficit (Global Footprint Network, 2018). Negatively impacting the environment is apparent to be a subject of urgency and will conceivably remain problematic for future generations. However, progress is apparent in the implementation of various environmental policies and has driven the environment in Europe to what is to be claimed ”*as good a state as the start of industrialization*” (European Environment Agency, 2016). Unfortunately, policies are not meeting climate benchmarks. Behavior regarding production and consumption patterns lay the basis for the current climate problem. Despite improving the efficiency in material use, the European consumption levels are still very resource intensive (European Environment Agency, 2016). Raising the question to whether the current methods of salvaging are going to be adequate in counteracting raw material depletion. Have we reached the limit of feasibility when recycling and re-using? As a major contributor of emissions and raw-material use, the construction industry is a given benefactor in limiting the environmental impacts.

”Our planet is finite, but human possibilities are not” - Mathis Wackernagel

1.1 Background

Industrialization, economic development and population growth have led to a push in the need for diversifying the outcome of ”end-of-life” materials. Figures for the European domestic market (Europe 2000-2012) show that raw material use is still strongly linked to consumption trends (European Environment Agency, 2016).

The 7th environment action program was adopted by the European union with the aim of ”living well, within the limits of our planet” and is intended to guide EU in the work on environment and climate change and achieve the vision for 2050 (European Environment Agency, 2013). The vision of 2050 includes the implementation of a circular economy ”where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience” (European Environment Agency, 2013).

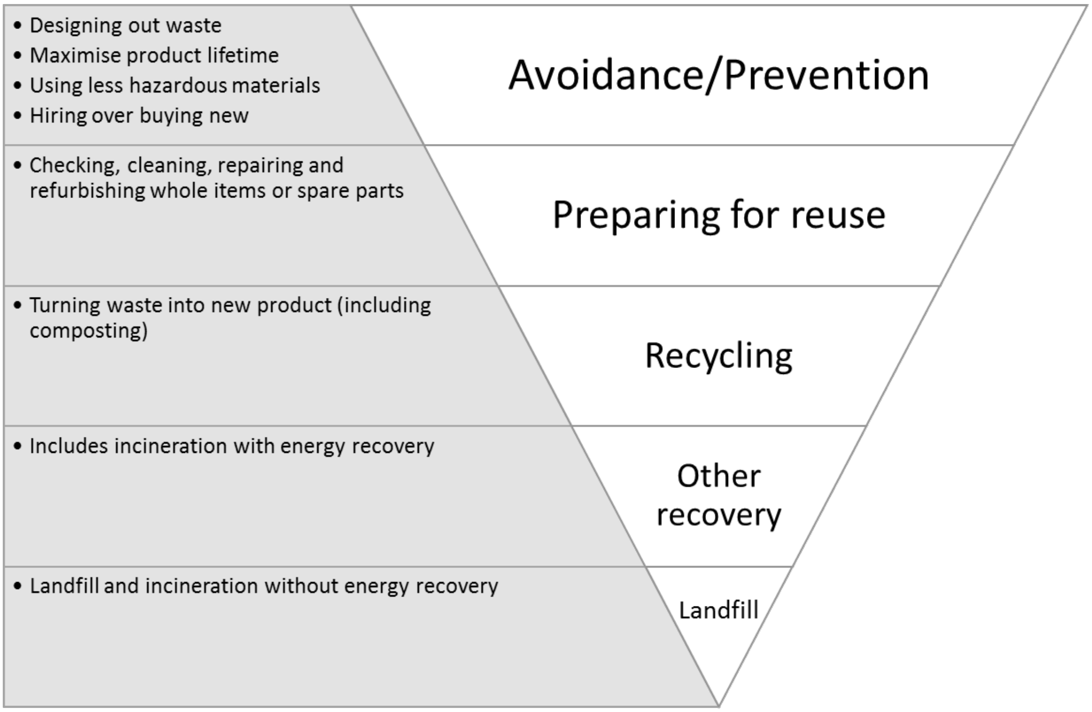

Figure 1 – Illustration of "Directive 2008/98/EC waste hierarchy". Waste management and prevention program

In their 2015 "State of the environment report" (SOER 2015), the European Environmental Agency (EEA) presents that new plans and ambitious political strategies are necessary to reach the vision for 2050 (European Environment Agency, 2016). This is linked to the "Waste Framework Directive" (Directive 2008/98/EC) presented by the Academy of European Law cooperation in 2009 and aims to stimulate reuse instead of recycling by promoting the incentive of reducing landfill demands (see figure 1) and thereby potentially lowering impacts of production (European Commission, 2016). However, enforcing the reuse of materials requires a full product lifecycle and not solely focus on "end-of-life" stage. Stated factors from the SOER 2015 include design, useful lifespan, reuse of parts, repair and recycling (European Environment Agency, 2016).

In combination with EU's policies and directives it is clear that there is a need for change in regards to the current material flows. Transforming the linear to a circular material flow is considered a reasonable step when evaluating the sustainability aspect of the material process. Building regulations are pressuring the construction industry to build more low energy structures, and despite decreasing energy use for the operational phase, it raises the importance regarding the proportion of added material. The embodied energy in materials and fittings is becoming an increasingly substantial aspect in the overall environmental impact of buildings. Climbing the waste hierarchy one, preferably two steps is seen as desirable before overcoming current environmental barriers and gain a sustainable society. However, there are many instances being affected by shifting to a circular model and it is of importance to the project that technical, environmental and financial aspects are investigated.

1.2 Research questions

This report will be striving to clarify the problems and limitations related to the circular flow of materials in the construction industry. Also, it will illuminate the means necessary to implement such workflows. By first locating suitable materials and components, the viability of reuse in building materials can be investigated for different cases. It is of importance to the project, that observations include the whole value chain and instances of which a material or component is likely to get exposed in a circular economy model. Also, it is reasonable to assume the potential ”user” and the potential ”recycler” of reused building materials will be facing different problems within the process. As many aspects of the building sector, costs are a subject of interest. What are the financial aspects of reusing building materials and how will it affect the general cost of building? Is the industry ready to adopt the circular material flow and how will it be implemented? Leading further into aspect of regulations and incentives of the industry. How do municipalities respond to reused materials in a building permit application? How will this affect the architectural aspects? It is undoubtedly a complex subject with many uncertainties and enquiries. Especially regarding warranties and material properties. How can material properties be guaranteed? What is the manufacture’s role in this and what can be said about warranties?

1.4 **Aim**

The aim of the study is to illuminate the efforts necessary to create a circular component flow in the Swedish construction industry (see figure 2). The means necessary to go from a traditional model to a circular is investigated.

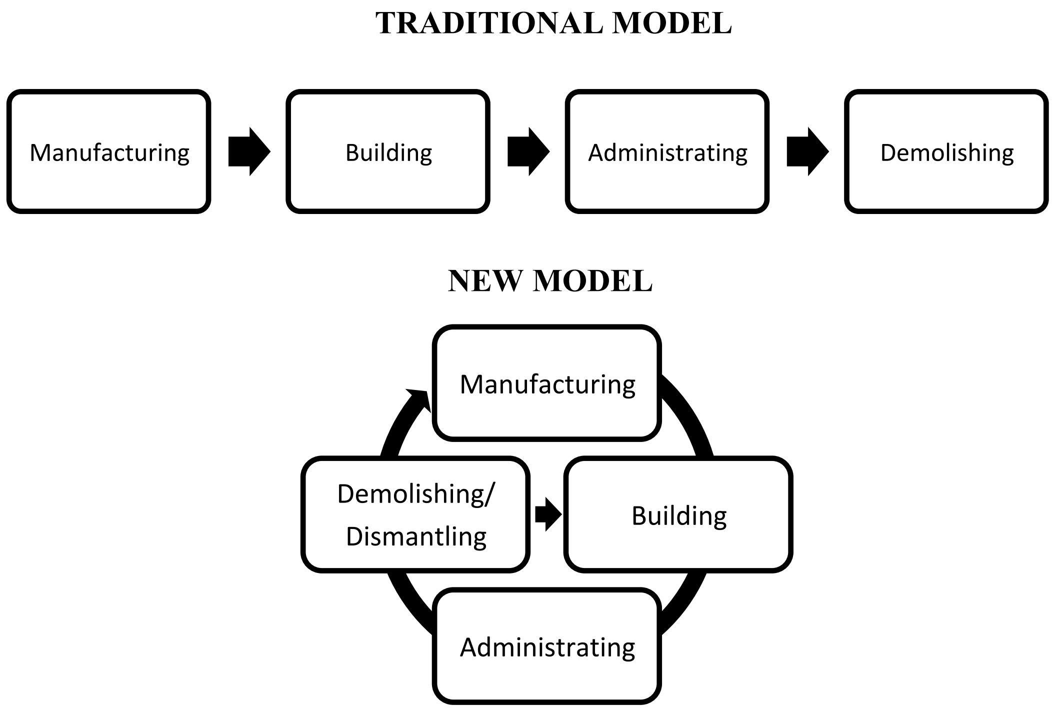

Figure 2 - Closed loop system for materials/components/systems. Illustrates the difference between traditional and circular building workflows.

1.5 **Objective**

The objective of the study is to provide a basis for a restructuring in processes related to reuse of building components and clarify the efforts needed in terms of technical, financial and environmental aspects. This correlates to the following;

- Evaluate the relevance and conditions for re-using materials, components and systems in buildings and determine if there is a possibility to implement a reuse strategy.
- Clarify how the potential reuse of materials, components and systems affect the building process and involved actors.
- Evaluate how to ”close the loop” (see figure 2) for the most significant material, component or system.
- Study the flexibility of re-using materials, components and systems regarding building regulations.

The project is structured into three parts; technical, financial and feasibility aspects.

1.6 Limitations

This study is limited to Sweden regarding financial, environmental aspects as well laws and regulations. The project is limited to building components and fittings. The materials are evaluated to be dismantled and reused as they are, or with minor alterations, for the same or ”inferior” purpose. The focus is on the commercial market.

1.7 Report structure

The report is divided into three main parts and is initiated with an introductory background. This is followed by an investigatory chapter with choice of method and presentation of results. The reports final part consists of an analytical discussion and is finalized by conclusion.

Chapter 1 Introduction – This part consists of a background introductory to the problematization of the subject. The chapter aims to give a clear overview of what is to be assessed in the report. The aim and objective together with delimitations are presented.

Chapter 2 Theoretical framework – This chapter is aimed to enlighten the reader of important terms and theoretical facts regarding the field of study. Prior research is assessed presented.

Chapter 3 Methodology – This chapter addresses the methods used to successfully discourse the aim and objectives of the study. The validity and reliability of the methods of choice is discussed and presented together with the status of primary- and secondary-data.

Chapter 4 Results & Discussion – This chapter presents, to the study, relevant findings. The section consists of summaries from surveys and interviews in combination with the procedure of quantifying qualitative parameters. The illuminated findings of the report are presented in combination with thoughts and opinions.

Chapter 5 Conclusion – This chapter is the finalizing part of the study. The objective of the thesis is validated and suggestions on findings are presented. Proposals for further research is presented.

2 Theoretical framework

This chapter presents theoretical background relevant to the subject.

2.1 Reuse, recycle and repurpose

When a product, material or component has reached the end-of-life stage, it is important to make clarifications in regard to the terms commonly used in the following stage. The terms reuse, recycle, repurpose, landfill or incineration are the options for this category. Landfill, which is the lowest in the hierarchy, is simply placing what is considered waste in large piles, sometimes covering it with soil. Incineration is a way of utilizing the embodied energy of the wasted material and simultaneously decreasing the need for landfill. This option, although recovering energy, is related to toxic gas emissions and byproducts of combustion (Vefago & Avellaneda, 2012).

Materials that have reached their end-of-life (EOL) stage will be addressed in accordance to the categories presented by Verfago & Avellaneda in their paper ”Recycling concepts and the index of recyclability of building materials” (Vefago & Avellaneda, 2012). The categories presented there are; recycled, infra-cycled, reused and infra-used.

Table 1 - Definition of terms in EOL materials.

	Definition
Landfill	• Disposal of waste trough burial.
Incineration	• Destruction of waste trough combustion • With or without heat recovery.
Recycle	• Passes through at least one chemical transformation of its internal structure or changes its physical state. • Maintains its initial properties.
Infra-cycled	• Subject to at least one chemical transformation of its internal structure or change in physical state. • Decreases its initial properties.
Reuse	• Does not pass through any chemical transformation. • Maintains internal structure, initial properties and physical state.
Infra-used	• Excluded from undergoing any chemical transformation. • Maintains internal structure, initial properties and physical state. • Subject to reduced initial properties and does not serve the same purpose as the previous lifecycle.

A recycled material or component is presented as an element passed through at least one chemical transformation of its internal structure or changes in its physical state while maintaining its initial properties. The material does not need to serve the same function as in its past lifecycle. Similarly, an infra-cycled material or component is subject to at least one chemical transformation of its internal structure or changes its physical state. But in contrary decreases its initial properties. The reused category is defined as a material or component that does not pass through any chemical transformation its internal structure and maintains its physical state. Maintaining its initial properties, the material or component is not restricted to serve the same function as its previous lifecycle. An infra-used material or component is similarly excluded from undergoing any chemical transformation of its internal structure or change in physical state. Instead it subject to reduced initial properties and does not serve the same purpose as the previous lifecycle. An infra-cycled material could be exemplified as brick, crushed and used as aggregate for new concrete (Vefago & Avellaneda, 2012).

The reuse category can roughly be sectioned into three subcategories; the first being ”direct use”, where the component is used with almost no preparation or alteration. The second is ”renewed reuse”, components are only slightly altered with reparation, cleaning or refurbishing. The third subcategory is ”rethought reuse”, where materials are combined to create a new product with a new function. (Gorgolewski, 2018)

It is also common to talk about downcycling when addressing the subject of reuse or recycle. The term is defined as the process of transforming EOL material into products of inferior quality compared to its original purpose, i.e. brick or concrete being crushed into aggregate (Haas, et al., 2015). Downcycling is therefore not easily distinguished from re-cycling and should be used only to describe the relation between the first and secondary circle of the product. In contrary, one can refer to the opposite process as upcycling.

2.1.1 The Delft Ladder

The Delft Ladder is a waste management strategy developed in the Netherlands with the purpose of reducing waste. It is applicable to individual product as well as industries (Gorgolewski, 2018). The ladder follows a ”top-down” process but is flexible and can be altered in accordance to the results of calculations i.e. Life Cycle Analysis (LCA) (Dorsthorst & Kowalczyk, 2003).

Table 2 - Definition of the Delft Ladder

THE DELFT LADDER	
Prevention	Choosing materials, components and methods to avoid waste.
Building reuse/renovation	Improving existing structures to avoid creating new materials for new buildings.
Component reuse	Taking apart the structure to reuse individual components.
Material reuse	Taking apart a component to reuse materials. Re-cycling what cannot be reused.
Useful new application	Re-using element or material for a new purpose, also known as downcycling/upcycling.
Immobilization with useful application	Turning a potentially harmful material or bi-product into a new non-harmful material.
Immobilization	Turning a potentially damaging material to harmless before landfill.
Incineration with energy recovery	Burning waste materials and recovering energy.
Incineration	Burning waste materials.
Landfill	Storing waste in piles, covered or uncovered

2.1.2 Designing for Disassembly (DfD)

Most products manufactured today are not designed to become parts in a circular manufacturing process (McDonough & Braungart, 2009). The concept of Designing for Disassembly (DfD) is a way of prolonging the usefulness of components and materials. Studies have been conducted by several researchers on the success factors and barriers of DfD methods. Akinade, et al. (2017) performed a literature review and identified three categories of critical success factors for the DfD process to be ”material related factors”, ”design related factors” and ”human related factors”.

In their own research, consisting of workshops, they identify five success factors (Akinade, et al., 2017);

- Stringent legislation and policy
- Deconstruction design process and competencies
- Design for material recovery
- Design for material reuse
- Design for building flexibility

The barriers of DfD is another aspect studied by several researchers, among these, Kibert & Chini (2000) identified the eight following challenges in the DfD process;

- Existing buildings have not been designed for disassembly.
- Building components have not been designed for disassembly.
- Tools for deconstructing existing buildings often do not exist
- Disposal costs for demolition is waste are frequently low.
- Dismantling of buildings requires additional time.
- Re-certifications of used components are often not possible.
- Building codes often do not address the reuse if building components.
- The economic and environmental benefits are not well established.

Rios, Chong and Grau (2015) state that building professionals find it extremely challenging to integrate the DfD concepts into their designs as they do not have the freedom and control over project schedule and cost in combination with facing non-availability of materials. Concluding that stakeholder's practices, perceptions and methods of delivery need to be changed (Cruz Rios, et al., 2015). A similar conclusion is reached by Kimber & Chini (2000), who defined the main problem facing deconstruction today, to be the fact that architects and builders of the past visualized their creations as being permanent and did not make necessities for future disassembly (Kibert & Chini, 2000). Nordby et al. presents strategies and principles to simplify the DfD concept. Their findings are sectioned into six main categories (Nordby, et al., 2008);

- ”Limited material selection” – By decreasing the amount of varied materials, the risk of having to replace the whole component due to depletion in one material is minimized. The use of mono-material components (homogenous material throughout) can increase the re-usability of the component due to avoided risk for contamination. Also, this results in fewer fractions of waste when the component is to be recycled.
- ”Durable design” – The idea of reusing products puts extra emphasis on the materials characteristics and the tolerance of joints due to removal and reinstallation. On a broader aspect, a durable design can also be linked to the flexibility of the layout of a building.
- ”High generality” – Refers to the standardization of dimensions, modular construction and standard structural grids. A building with high generality is

adaptable to change its functionality within existing floor plans and ceiling heights. High generality is also achieved by reducing the complexity and creating small scale lightweight components, allowing for architectural flexibility.

- ”Flexible and reversible connections” – This is presented as a fundamental part of the DfD process. The idea suggests the use of mechanical connections before chemical bonding due to the problematization of damaging components in disassembly.
- ”Suitable layering” – The theory elaborates on the observations that various parts or layers of the building is subject to different rates of replacement and should be designed so that each layer is made structurally independent and arranged on expected lifespan, making each component exchangeable.
- ”Accessible information” - Addresses the importance of building and component information availability to comply with demands for future reuse. Tools for addressing the conservation of information are presented as logs, drawings and guides for deconstruction as well as various types of material and component tagging.

Conclusively, Nordby et al. argue that presented strategies lead to an ”architectural manifest of sustainable thinking” in the construction of buildings. Hence, leading to more localized and restricted material selection, highlighting not only the materials but also the arrangement and installation (Nordby, et al., 2008).

2.2 Circular economy

Circular economy is a theoretic concept adapted by economists for decades. The basic principle is rooted in the idea of creating activities based on using renewable resources, within the limits of availability and without causing environmental degradation. The initial concept is thought to be created in the 1970s and arguably laid the foundation of the circular economy model (Hebel, et al., 2014). This has, on later days, been developed into the concept of how materials used in industrial processes should be seen as elements of a continual circular process as in the natural metabolic life cycle (McDonough & Braungart, 2009). The term is also known as ”cradle to cradle” and was first coined by architect and industrial analyst Walter R. Stahel (Ellen Macarthur Foundation, 2018).

Walter R. Stahel introduced the concepts of product-life extension activities; reuse, repair, reconditioning and recycle. Stahel claims, the smaller a loop is made (see figure 3), the more beneficial the outcome, due to reduced material use. He argues that the energy of manufacturing allows to be exchanged for manual labor, leading to innumerable business opportunities and substantial reduction in both unemployment and poverty (Stahel, 1982). Stahel writes; ”Do not recondition something that can be repaired, do not recycle a product that can be reconditioned economically”.

The circular model has been increasingly popular in later years. The current consequences of a linear ”take, make, waste” approach has been noticed by governments and policy makers as apparent to be unsustainable (The British Standards Institution, 2017). In contrast, a circular economy maintains resources within the economy for as long as possible by reuse, recycling and remanufacturing (LWRB, 2017). Figure 3 illustrates how a circular economy can be divided into loops of ”consumers” and ”users” and were the nature of the process determines the restraints of the loops. The biological cycles are designed to ”feed” back to the system through processes like composting. Whereas technical cycles recover and restore through strategies like reuse, prolonging/maintaining and remanufacturing. The labor and material intensities are linked to the size of the loops presented, were a small loop is very material effective but labor intensive (Ellen Macarthur Foundation, 2017).

With an additional three billion middleclass consumers expected by 2030, growing urbanization and population, the focus on circularity is apparent to stay (Gorgolewski, 2018). The circular approach is thought to have positive impacts in overcoming the pressures on diminishing resources. In their 2017 ”London´s Circular Economy route map” the London Waste and Recycling Board (LWRB) present figures arguing that by adapting circular processes the city is expected to benefit from 40 000 new jobs and seven billion British pounds in net annual revenue by 2036. Together with financial and social gains, the circularity is argued to create a more stable operating environment, detached from costs related to fluctuations of material expenses (LWRB, 2017).

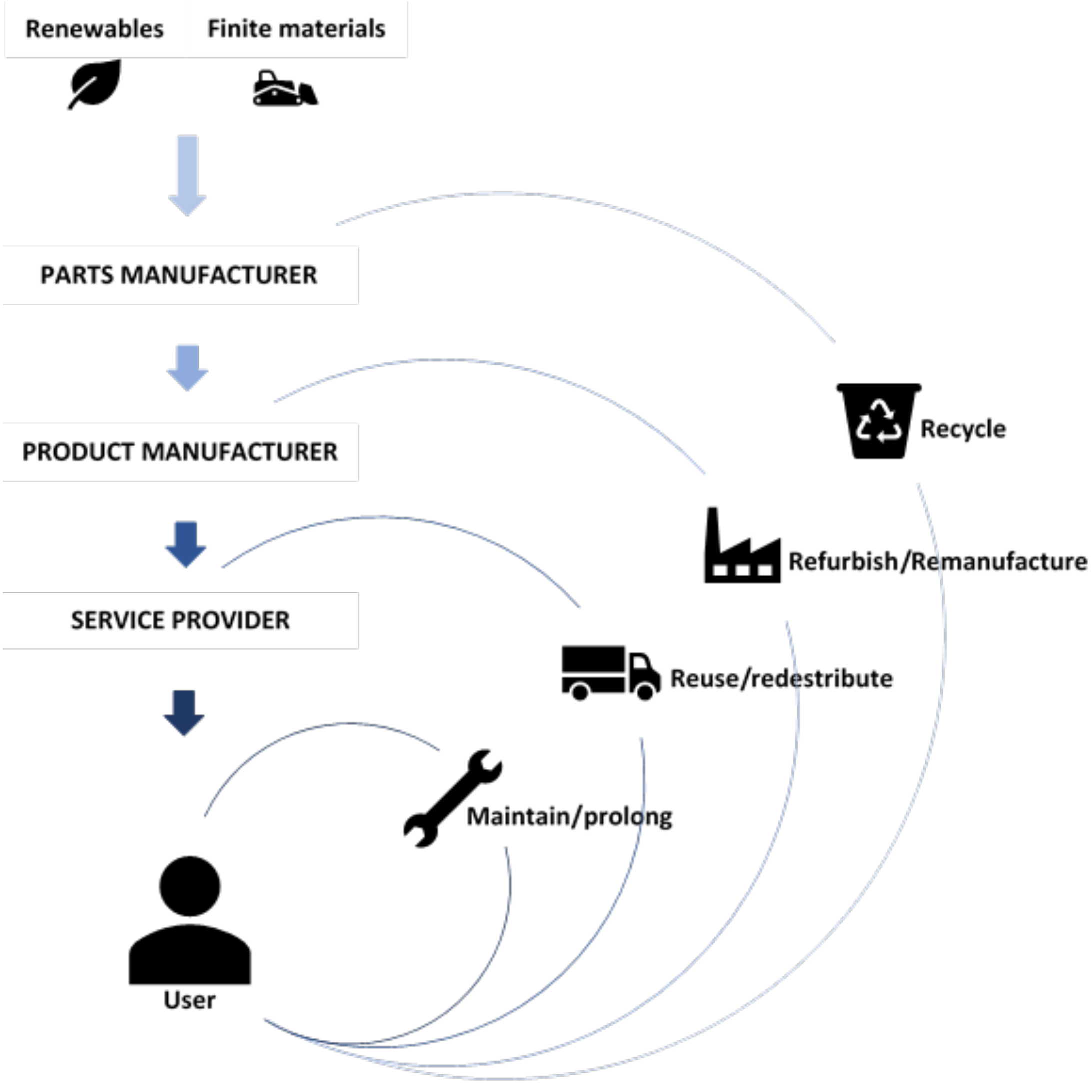

Figure 3 – Outline of a circular economy in product/material/component use.

2.3 Construction waste

The building sector in Sweden is responsible for approximately one third of all the waste generated (excluding waste from mining) and one fourth of contaminated waste (Swedish Environmental Protection Agency, 2017). This roughly correlates with the same figures for the EU in general (Swedish Environmental protection Agency, 2014).

2 503 Million tons of waste was generated annually by the 28 European countries (EU-28) according to figures from 2014 (Eurostat, 2017). This translates to around 479 kg of waste on average per citizen and has stayed roughly the same since the beginning of the analysis in 2004 (Swedish Environmental protection Agency, 2014).

Nearly half of the waste in 2014 (47.7 %) was disposed by means other than incineration. Another 36.2 % was sent to be recycled and approximately one tenth was used as backfill (use of waste in excavated areas for slope reclamation or engineering purposes in landscaping) leaving around 6 % for incineration. Only 4.7 % was burnt with heat recovery (Eurostat, 2017).

In regard to the hazardous waste, nearly half (49 %) was landfilled, an equivalent of 73 kg per inhabitant. Roughly 13 % was incinerated and around one third was recycled or used for backfilling in 2014 (Eurostat, 2017). But the general figures show decline from results in 2004. The recovered segment (incineration with recovery, recycled or used for backfilling) show growth by 23.4 % in 2014 compared to 2004. Also, the overall degree of recycling shows a rise (excluding waste from mining) by 2 % from 53 % in 2004 to 55 % in 2014 (Swedish Environmental protection Agency, 2014)

2.3.1 The Swedish waste industry and fractions

The Swedish waste sector is an open market, separated between commercial (30 %) and municipal (70 %) companies. Due to the competitive market the services variety depending on where in the country the operation is located. There are approximately 700 companies (in 2004) that diverge in size and ability to process types and quantities of waste. Among these, only 28 are connected to the district heating system and have facilities for incineration. A majority of incineration plants are owned by, or in collaboration with municipalities. It is estimated that on average the incineration plants make half of the income from supplies energy to the grid and another half from fraction fees (Swedish Environmental Protection Agency, 2004). All companies work with some form of on-site sorting and charge dumping fees based on the nature of fractions being delivered. The prices on fraction vary depending on homogeneity and type of waste, i.e. a mixed fraction is often more expensive to dump due to the process of separation in the recycling plant. The companies have different services linked to the fractions. Some deliver their own containers to the site and charge based on used unit and some provide dumping services, charging by delivered ton (Swedish Environmental Protection Agency, 2004). Prices also change depending on the recyclability of the material, if the product delivered has a high recyclability potential and an aftermarket value, the prices for that fraction is lower.

2.3.2 Import and export of waste

The Swedish import of waste has been growing steady since 2008 and is estimated to be around 2.5 million tons in figures for 2014. The export for the same year is around 400 000 tons (Statistics Sweden, 2000-2014). The imported waste serves two functions; financial and environmental. Charging fees to the exporting countries generates income, and by incinerating the imported waste the region can benefit from district heating, hence expanding profit margins for the product. Secondly, by importing and incinerating waste, what otherwise would lead to landfill and the release of methane gases can be avoided (Sysav, 2017). Sydsav AB is a waste management company in south of Sweden owned by fourteen municipalities in the region. Their main facility in Malmö is equipped with an incineration plant and provides approximately 60 % of the district heating demand in the adjacent region. The company reports that 58 431 tons of combustible waste was imported from Norway and Great Brian in 2016. This is around 10 % of the total waste going in to the burners in that year. Regional figures show that around 20 % of the waste in Sweden is imported (Sydsav AB, 2017). It is unclear how much additional income is associated with burning of imported waste.

2.4 The process of demolishing

Demolition can roughly be defined as the systematic, total or partial removal of structural systems, subsystems and materials from a building. The practice of demolishing has undergone some changes in the last decades. In order to comply with health and safety regulations in combination with commercial interests, the process has become more machine-intensive and workflow is designed to stream material towards recycling rather than reuse (Addis, 2006). Figures from ”Statistics Sweden” (see figure 4) show a substantial gap between the number of new and demolished residential buildings in Sweden. The data includes both single and multifamily buildings. The gap is explained by ongoing housing crisis. Estimates show that around 255 municipalities (out of 290) have a housing deficit that is expected to remain to year 2020 (Boverket, 2017).

Figure 4 - Statistics from SCB of newly built apartments and demolished apartments from 1991 – 2016

2.4.1 Demolition laws and regulations

The demolition process is regulated by law in many countries and requires approval from a government function. In Sweden, the process of demolishing or ”altering a building to a great extent”, requires a formal application including various details of the structure of interest (if the building is located within the detailed development plan). The term ”historical, cultural or artistic values” are often actualized when addressing buildings in relations to demolishing or renovations. The term is regulated in the ”Swedish building code” and is linked to alteration of the materials and attributes of the building. Alterations to a building of historical, cultural or artistic value has more restrictions to visual changes but less in terms of technical properties (Boverket, 2016).
The application includes appointing a supervisor to address subjects of hazardous waste and risks. The supervisor addresses matter of quality control and is required to do an inventory on all materials to be demolished, including classification of hazardous materials and how these are to be handled (Sveriges Riksdag, 2018). Demolition starts when the formal application has been approved and a notice of starting permit has been issued by the municipality.

The waste generated in the demolishing or dismantling of a structure is regulated in the ”Swedish environmental code” (Miljöbalk 1998:808). The law states that generated waste, excluding dangerous waste, is to be handled in accordance to the waste hierarchy (see figure 1) when it is environmentally feasible and financially reasonable (Swedish Enviromental Protection Agency, 2017).

In Sweden the work environment is regulated by law. All identified aspects of health risks are addressed and aimed to be minimized. Work related to vibrating equipment and adequate working conditions are among some. Asbestos, being among some of the highest risks, requires additional effort when handling and discarding, failure to comply with the regulations are followed by fines. When encountering asbestos is building related situations a specially trained person is appointed to address the work in relation to the removal and discard of the masses. Further, all personnel in contact with the contaminated masses are to have knowledge and training of working with asbestos. This process also requires special permits issued by the Swedish Work Environmental Authority (Swedish Work Environment Authority, 2014).

2.4.2 Deconstruction and demolition techniques

The demolition stage can be divided into three main categories, progressive demolition, deliberate collapse mechanisms and deconstruction. The progressive demolition technique is designed to retain the structural integrity of the building and by controlled removal demolish sections and parts. This method is commonly used and preferred for demolishing in areas of confined space. This category can be further divided into; progressive demolition ”by hand”, ”by machine” and ”by balling”. The demolition carried out by hand is referred to as the operation of smaller machines and hand tools, such as cutters, impact hammers or cable cutters. When using heavy machinery, such as excavators with different attachments for crushing and shredding, it is referred to as demolition by machine. The third option is the method of suspending an iron ball and using it to knock down parts of the structure by repeated force on impact (Abdullah, et al., 2002).

Deliberate collapse mechanisms are used to target specific structural weak-point of a building in order to cause complete collapse. This method is used on structures located on isolated sites due to risks on surroundings and elevated spreading rates of dust and debris. The process involves using explosives or wire rope pulling (Abdullah, et al., 2002).

Deconstruction or selective dismantling can be seen as the reverse procedure of building. This workflow is usually detached from using heavy equipment and is labor intensive. This method is commonly used for smaller renovations or in preparation for a deliberate collapse of the structure. Dismantling a structure allows for the potential of more unified waste fractions and the possibility of reusing parts of the building (Abdullah, et al., 2002).

Cost for selective demolition is dependent on several factors. The method is thought to prolong the process with up to approximately 30 %. But the additional time is not necessarily linked at a same rate to a higher cost of dismantling in comparison to demolishing (Härle, et al., 1995). A case study performed by Danata et al. (2005) on the dismantling of six residential buildings in Massachusetts (USA) show a 17 % - 25 % increase in costs compared to traditional demolishing. The affecting cost are linked to labor costs, disposal costs and resale value of deconstructed materials (Dantata, et al., 2005). Similarly, a case study performed on The Federal Building in Winnipeg (Canada) summarizes key factors for successful dismantling. Boyle & Kyle (1999) identify the importance of planning, extended timeframe due to additional labor, inconsistency in policy issues and the importance of economic data collection as some of the key factors. Keeping track of financial figures are seen as necessary in order to have definite statements about the benefits of waste management. Also, transport is presented as a controlling issue, with the statement that whether for reuse or recycle, recovered materials command only a fraction of the value of its corresponding new part, making it highly sensitive to local conditions and infrastructure (Boyle & Kyle, 1999).

3 Methodology

This chapter clarifies approaches and aspects regarding the validity, reliability of results, and factors that may influence the outcome of the study.

3.1 Methodological approach

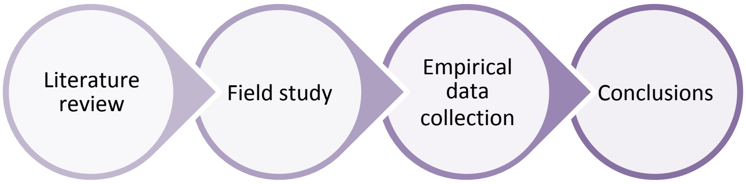

Figure 5 - Phases for methodical workflow and study layout

The method is divided into four phases (see figure 5); literature review, field study, empirical data collection and conclusions. Mainly qualitative approaches have been conducted to best discourse the subject and obtain data with high reliability and validity. Quantitative methods were used to verify findings from the field study. The methodological approach is regarded to be the most efficient way of assessing the problematization and related subjects.

3.2 Scientific approach

When understanding or learning something about reality, one can roughly operate in two contrasting scientific attitudes, positivism and hermeneutics and when reasoning we often refer to three methods of approach; deductive, inductive and abductive.
The study is thought to have both an inductive and a deductive method in addressing the problematization and the scientific approach is thought to be primarily hermeneutical. The qualitative nature of the problematization allows for wider understanding of the field when applying a hermeneutical method. This adds to the quality of the empirical status. The hermeneutical approach is qualitatively oriented and consists of understanding and interpreting systems. This research role is seen as open and subjectively involved. Although, the study is still influenced by a positivistic approach. The field study is linked to the testing of theories formed from the results of the pilot study and is very positivistic in the workflow. Positivism is a research role that is objective. The scientific anchoring procedures are usually quantitative and uses statistical methods for analysis (Patel & Davidson, 2003). A deductive approach is characterized by the fact that the researcher draws conclusions on individual phenomena based on existing theories and general principles (Patel &

Davidson, 2003). The reasoning flows from ”general” to ”specific”, starting with a theory and involves collecting observations in order to test the hypotheses, in other words, finding data to support and argument (Merriam-Webster, 2017). Working with a deductive approach provides indications and results at an early stage but is not without pros and cons. A clear disadvantage is the fact that the approach could lead the study in a misleading direction, if the first indications would be affected by abnormal values. Alternative methods could have been used for the data collection phase of the project but the ratio between material and resource allocation was the motivation of the choice of method. No other method was considered to have equal quality results in relation to resource utilization. In contrast, the inductive approach is based on the fact that the researcher studies a research object without first having anchored the study in the accepted theory. The reasoning moves from specific observations to broader generalizations, finding arguments to explain data. By detecting patterns and uniformities the researcher formulates a tentative hypothesis (Patel & Davidson, 2003).

The research is initiated with a field study that is strongly linked to an inductive method of reasoning. As the empirical data collection is based on the results from the field study, the approach is thought to be deductive. The study transfers from gathering observations to support data into validating data to support the argument. The disadvantages of working with observation-based research is that the result cannot be seen as completely untainted by the researcher's previous experiences and impressions. This could lead to the fact that the researcher unconsciously preferences observations or study objects on desired outcomes, hence leading to potential results never being noted. This is particularly delicate in the inductive part of the study, as this forms the basis for the study.

3.3 Data collection

The gathering of data is of specific status to the report and is methodically divided into two subcategories, primary- and secondary data. The primary data is of importance to the quality and generalizability of the study. Primary data is information gathered through interviews, questionnaires and clarifications. The data is collected directly from the primary source of information and is adapted to the problematization (Jacobsen, 2002). Primary data for the study consists of semi-structured interviews with different actors in the building process, calculations and a survey electronically distributed to all 290 municipalities in Sweden.

Information that has been gathered and is based on explanations from additional sources is referred to as secondary data. Secondary data includes existing synopses and can consist of both qualitative and quantitative data (Jacobsen, 2002). Secondary data for the study is comprised of findings from the projects theoretical reference frame. Information has been gathered through publications and loans from

Lund university library and databases such as LUBSearch, Google Scholar and SwePub.

3.4 Qualitative and quantitative research methodology

3.4.1 Interview

When conducting an interview, there are two aspects to consider, the degree of structure and degree of standardization. These parameters are usually chosen based on the aim and expected outcomes of the research. The degree of standardization is dependent on the freedom given to the interviewer on the design and arrangements of the questions. A non-standardized interview is conducted when a researcher independently verbalizes and varies the disposition of the questions depending on the person being interviewed (Patel & Davidson, 2003). An unstructured interview is suitable for explorative research and when the goal is to gain a descriptive understanding of a process or phenomenon (Ruane & Nilsson, 2005). The degree of structure determines the possibility for the respondent to freely answer a question. Strongly structured interviews are beneficial when the researcher aims to quantify data or wants to gain an overview of attitudes, behaviors, values etc. (Ruane & Nilsson, 2005).

The interviews were conducted by the authors and adapted to each respondent and the related work-field. The interviews conducted in person were restricted geographically to Skåne county in the south of Sweden. To best represent the respondent's answers, one interviewer took notes while the other asked the questions. The respondent was later asked to distribute a questionnaire within the company consisting of same questions as the interview. Nineteen interviews/surveys were conducted in total. Nine were conducted in person with both researchers present. Seven questionnaires were distributed via email to the respondents and two were conducted by telephone due to geographical location. In total, five manufacturers, two developers, one contractor, one architect, one head of department, two waste management specialists, two environmental specialists, one investigator from the housing commission and three project managers were interviewed.

The respondent was introduced to a short presentation of the purpose and general aim of what is to be assessed in the interview, together with an explanation of its status in the report. Confidentiality is stated to the respondent before the interview was started.
The interviews conducted were semi-structured and semi-standardized and based on predetermined questions. This creates flexibility and allows for complementary and in-depth questions to be added. The interviews vary in content and design due to the need for adapting the questionnaires to the profession of the respondent and the setting of which the interview was conducted. The questionnaires can be divided into two sorts; one more open to elaboration and one structured. The structured

questionnaire was used when interviewing manufacturers, due to the number of interviews conducted during one event. The questionnaire consists of eight questions and was filled by one interviewer as the other asked the questions. One assessment error that occurs during qualitative collection methods is referred to as ”the interviewer effect”. Meaning that the researcher during the information collection phase behaves in a way that the respondent, consciously or unconsciously, understands the researcher's expectations. This causes for the objectivity to be put out of play (Patel & Tebelius, 2003). This has been addressed through the proper formulation of questions, limiting the interviewer from asking ”leading” questions.

The survey was created using Google forms. This is a survey tool designed to perform online surveys. Google Inc. delivers features for compiling data at a level that is sufficient for the scope of this report. The tool also allows for better comparability between the respondents and for questionnaires to be distributed by email when needed. A summary of the questionnaires can be found in appendix 7.2.

3.4.2 Survey

A survey-study essentially comprises information collected through surveys or structured interviews conducted in more than one case and at a certain time in order to obtain a series of quantitative and quantifiable data relating to two or more variables and is analyzed with the purpose of finding relatable patterns (Bryman & Bell, 2011).

The survey consisting of 14 questions has been distributed via e-mail to all 290 municipalities in Sweden. The request was sent in two sequences, one of which is a reminder. The reminder was sent ten days after the initial request. The e-mail addresses used for contacting the municipalities varied with a mix of person-specific and general e-mail addresses. The survey can be found in appendix 7.1.

After the initial screening questions, the respondents were presented with BBR table 9:2 and 9:2a, together with advisory text linked to windows. The respondents were then presented with calculation for four fictive houses located in Lund (see table 3). The houses all have the same area, window-to-wall ratio (WWR), air-leakage, thermal bridges etc. In BBR, there are U-values that are presented as ”values to aim for”, these differ depending on the various parts of a building, such as walls, slab, windows etc. and are mainly purposed for renovations. The values are not in any way considered as regulation and is presented as guiding values. The energy performance of a new building is regulated by three values in BBR, the ”installed effect ($4\ 500\ \mathrm{W}$ for buildings with heated area below $130\ \mathrm{m}^2$)”, ”average U-value ($0.4\ \mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})$)” and ”primary energy ($\mathrm{EP}_{\mathrm{pet}} = 81\ \mathrm{kWh}/\mathrm{m}^2$ for Lund)”. All three must be fulfilled in order to be eligible for a ”starting clearance” from the building commission. The four houses presented in the survey were designed to test the flexibility of the guidelines and regulations of BBR. Deliberately, ”aim values” for windows in BBR were not fulfilled in any of the cases. ”House 1” was knowingly presented with unsatisfactory figures for the EP_{pet} in order to spot deviating responses.

The main motivation for choosing a survey is the low resource utilization per response, as the survey can be distributed to a large number of participants with ease. Also, digital surveys allow the participation to be almost unlimited, both in terms of number and geographical spread. It also gives the respondent freedom to choose when to answer the survey, which contributes to increased number of respondents (Ejlertsson, 2011).

Surveys provide limited opportunity for complicated questions and spontaneous follow-up questions, which would lead to deeper understanding of the subject. The standardization is often high in a survey, meaning that all questions and options are the same for all respondents. A high standardization allows for easy- to-understand results (Ejlertsson, 2011).

The survey was designed based on achieving simplicity in language, not to be leading and consist of unambiguous questions. The graphic design and choose of color was in regard to simplicity and minimizing distractions. Special attention was given to achieve symmetry in the answers, i.e. same number of ”Yes” and ”No” answers. Disadvantages of conducting a web-based survey is mainly regarding the email addresses. It is often difficult to determine whether the survey reached the intended person or if has been discarded by the recipient. Technical difficulties also increase the loss of responses. The survey as a tool is also limiting in regard to the design of questions that can be included, some types of questions are simply unsuitable in a survey. The number of questions and length of the survey is also important when addressing the response rate. A lengthy survey without any compensation can lead to a low response rate.

3.4.3 Sample

A group of individuals that are the target for a survey is commonly called a population (Ejlertsson, 2011). A selection or sample includes a balanced cross-section of all cases relevant to the population. To be representative, the sample must include all relevant types to the population and also include these in proportion to the population as a whole. The researcher can, based on already known key features in a population, intentionally make a sample or selection that is proportionally truthful and likely to characterize the target population. This is called ”proportionally stratified selection” (Denscombe, 2004). This type of sampling technique provides a relatively homogenous selection and increases the probability that the final sample will be representative. If a population is thought to be heterogenous, more elements are considered necessary in order for the sample to reflect the entire population.

Since the survey was directed to all municipalities in Sweden it is thought to result in the population being the sample, or also called a total-survey. Hence, there can be no selection technique since the entire population is being examined. However, the reference frame within the population can be defined as a ”non-random stratified selection method”, meaning the individuals are pursued based on their knowledge and skills. The reference frame for the pursued individuals was loosely defined as ”To individuals working with the technical requirements in BBR”. This is aimed to the building committee and is considered to have a small spread within the professionals in this category.

When selecting actors in the building sector for qualitative interviews, the size (number of employees) and the geographical location of their business was the decisive factor. To promote the best possible basis for the outcome, the largest companies in Skåne were the focus of the study

3.4.4 Processing of qualitative and quantitative data

Methods that require the researcher to have an active role in the registration of the information is subject to misinterpretation errors. This means that the researchers assessment differs from the ”true” value of the information. Since the project is subject to both qualitative and quantitative research methodologies, the work is considered to be affected by both types of commonly occurring sources of error. The collection and processing of data has involved several manual instances and has been intended extensively to prevent expectations and opinions from coloring the results, but despite careful work the context can not be eliminated. The effort of structuring data aims to create unity in the material without affecting the content. All processing of data that allows room for interpretation by the researcher has been addressed in pairs to avoid putting the reliability of the material at stake. Much of the gathered data was subject to some form of structuring with the intent of creating an overview of the findings. Using a less complicated coding scheme, open questions have been categorized with numerical values based on the content of the specified answer. Content that was processed in preparation to be presented in chart and table form, involved deleting responses that do not form the basis of the statistics and can be considered as "no response" or internal loss. The ”halo-effect” is a term used to describe one of these misinterpretation phenomena. The theory states that the first impression that the researcher is exposed to will influence the researchers' assessment throughout the rest of the registration. Meaning, the researcher gets a predetermined view of the outcome and this affects the result. Information and tools that provide numerical results are less exposed to risk of distortion during the collection phase in comparison to techniques that rely on the researcher's inputs, i.e. observations and interviews (Patel & Tebelius, 2003).

When interpreting and processing information it is important to address vagueness and bias. Vagueness is related to non-systematic errors in the measurement process. Meaning that there is no definite reason to the occurrence of the error included in the measurement, but rather a result of chance. This can be a result of i.e. poorly constructed questions, the respondent's inattention or the researcher's influence. Biases are connected to systematic errors and follow a certain pattern. The errors in the measurement process are consistent and follow a certain direction. Bias is commonly linked to the researcher's preconceived understanding of the problem. Meaning that the researcher can interoperate uncertainties or ambiguous answers in accordance to the researcher's expectations (Ruane & Nilsson, 2005). Sections of the study sensitive to interpretation has been limited and remaining parts have been assessed with other methods in an attempt to minimize errors. The objectivity of the report is thought to be high due to the advantage of working in pairs. The researcher's options and views are then subject to questioning. Also, material that is open for interpretation has been presented in accordance of complying with the greatest possible extent of insight. Hence, it is believed that good scientific practice has been exercised and the material has been presented truthfully.

3.4.5 Loss

One of the most common constraints in surveys is a large loss. Losses are considered a source of error that does not concern the selection process itself but may occur when choosing individuals. Some individuals may be unable to provide the requested information or simply refuse. Another major loss can be related to the inability to contact the individual. A large loss can lead to an increase in the risk of errors and misconceptions. This problem is primarily relevant to surveys and the researcher often tends to increase the validity trough triangulation, i.e. use of several methods of measurement (Bryman & Bell, 2011).

The measures taken to minimize the loss in the survey was mainly focused on striving for clarity in the questions and avoiding ”open” questions, questions where the respondent can answer freely. The accompanying letter was conducted with the purpose of reflecting the seriousness of the survey and give a quick overview of what is requested. The survey was designed to be as short as possible and a reminder was distributed to the recipients ten days after the initial request. The biggest source of loss is considered to be the quality of email addresses. All the emails were retrieved from the municipalities websites and varied on general and person-specific emails. The difficulty of knowing the rate of deliverance to the intended participants make it hard to assess the loss due to technical issues.

3.5 Generalizability, reliability and validity analysis

Generalization involves conducting conclusions about an entire category or population based in the outcome of specific instances. The generalizability in a result is related to whether individual cases of samples can be formulated into claims regarding the nature of the whole category (Denscombe, 2004).

There are difficulties in generalizing the qualitative findings of the study. Due to both limitations in content and geographical spread it is not found to be strongly generalizable. Content and concurrent validity are two methods of investigating whether the findings represent what is intended to be measured. A high content validity indicates that the process from theory to individual questions has reached a good coverage of the studied field. Variables are often formed based on literature studies, which, based on relevant concepts of the problem, can be formulated into questions. The questions are then used as the measuring tool for acquiring the desired information. Concurrent validity means that the outcome of a certain measurement is checked based on another criterion. By using another technique to study the same object, the function of the measurement technique is evaluated (Patel & Davidson, 2003). The study is thought to have both high content and concurrent validity. Results from interviews are compared to findings from questions distributed as a questionnaire within the respondent's company. By using quantitative methods in parallel with interviews, the validity of the results can be strengthened while creating deeper understanding of the research question. Internal and external validity is also an aspect of importance. Achieving internal validity indicates that the variables are interdependent and subject to change. External validity refers to whether the material is generalizable towards the sample (Patel & Davidson, 2003).

There are clear relationships between observations and the empirical material as well as the theory, which indicates good internal validity. In regard to the external validity of the survey, there are difficulties in determining how well each question was designed. Since all respondents answered under different circumstances and with varying background, there is no way of stating anything about the external validity. Still, there are no clear indications that any of the questions have been perceived as challenging. In addition to the validity, it is applicable to investigate the reliability of the findings. A result is considered to have high reliability if repeated measurements indicate the same outcome, provided that no change has taken place in the variables being measured (Patel & Davidson, 2003). The reliability of the material is considered to be good. A majority of several independent results showed a good correlation and the respondents are seen as knowledgeable within their respective field.

3.6 Case study ”The house”

A fictive house was picked based on an average Swedish villa as a reference in calculations and survey, allowing for comparability in the results. The house was placed in Lund with an average yearly temperature of 9 °C and ”dimensioning winter outdoor temperature” (DVUT) of –9.8 °C. Thermal bridges were thought to increase U-vales by 25 % and the house was primarily heated with electricity due to the simplifications in comparability when addressing LCA and LCC. Also, this is seen as one of the less environmentally friendly heating options. The base case was used in calculations regarding life cycle cost (LCC), life cycle assessment (LCA) and in the survey distributed to the Swedish municipalities.

Table 3 - Values of the fictive house used for calculations and survey.

HOUSE PARAMETERS	
Living space	$117\ m^2$
Area (Interior walls)	$110\ m^2$
Area (Interior roof)	$117\ m^2$
Area (Windows 1.2 · 1.2 m)	$26\ m^2$
Window-to-wall ratio (WWR)	24 %
Air-leakage	$0.6\ l/(s \cdot m^2)$
Heat recovery	80 %
Heating source (Electricity)	1 SEK/kWh

	House 1	**House 2**	**House 3**	**House 4**
U_{Roof} $/(W/(m^2 \cdot K))$	0.13	0.097 5	0.084	0.975
U_{Wall} $/(W/(m^2 \cdot K))$	0.18	0.135	0.1	0.135
U_{Slab} $/(W/(m^2 \cdot K))$	0.15	0.112 5	0.08	0.112 5
U_{Doors} $/(W/(m^2 \cdot K))$	1.2	0.9	0.65	0.9
$U_{Windows}$ $/(W/(m^2 \cdot K))$	2	2	2	1.5
EP_{pet} / (kWh/m^2))	86	77	70	69
Installed power / W	3 812	3 385	2 960	3 049
$U_{Average}$ $/(W/(m^2 \cdot K))$	0.37	0.33	0.29	0.28

Thermal properties were varied in four different cases presented in table 3. The first house (House 1) was designed to not comply with the directions in the Swedish building regulations. The following two house-types, house 2 and 3, have a reduction in thermal properties with 25 % for house 2 and 35 % for house 3, compared to house 1. House 4 was only used in the survey to see if improving the U-value of the windows would change the response patterns. The U-values were chosen from the major manufacturers (in Sweden) of the various components.

3.7 Calculations

Complete calculations regarding LCA and LCC can be found in appendix 7.3 and 7.4.

3.7.1 LCA

To compare new windows with reused windows during the operational phase, the energy calculation from the fictive house was used. The U-value for the fictive house was changed to 1.1 $W/(m^2 \cdot K)$ and the energy calculations were repeated. The LCA estimations were compounded from a cradle-to-gate scenario and correlates to product stage A1-A3 and B1, including ”raw material supply”, ”transport of raw materials to factory”, ”manufacturing” and ”Use” as presented in standard EN 15804 (EeBGuide Project, 2012). Transport from the factory was not included, due to generalizability in the presented values. Transport is thought to occur in both cases of buying new and reused materials. The environmental impact of transport accounts for around 10 % of the total CO_2 emissions (European Envionment Agency, 2017) and is not considered to have significant impact on LCA calculations. The restoration of materials ”on-site” is a possibility, this is not considered to be ”worst case scenario” and is therefore discarded in the estimations. The LCA estimations were based on finding from the EPD (Environmental Product Declaration) database ”Environdec”. No accurate EPD could be found for a comparable window. Instead a selection of different EPDs were combined to best represent an energy efficient window.

Table 4 - Sources for EPDs.

Material/Component	Company	Reference
Steel	Steel Color	Table: Patterned Sheet, page 16 (Envirodec, 2016)
Timber	Wood Solutions	Table 8: Environmental impact, page 12 (Environdec, 2015)
Aluminum	Purso	Table: Potential environmental impact, page 15 (Environdec, 2018)
PVC/Rubber	ODE	Table: Environmental impacts for ODE R-flex, page 11 (Environdec, 2016)
Glass	Saint-Gobain	Table: Environmental impacts, page 15 (Environdec, 2016)
Window Properties	Elitfönster	Table 4: Innehåll, page 1-2 (Elitfönster, 2017)
Manufacturing (A3)	Zuhaizki	Table: Summary, page 9 (Environdec, 2018)

A typical low-energy window was picked from one of Sweden's largest window manufacturers. The material content of the window was identified using available information from the manufacturer. Due to large variations in environmental impact from different energy providers, three sources from various parts of the spectrum was included. Figures from Electricity Map (Electricity Map, 2018), Vattenfall (Vattenfall, 2018) and Energirådgivningen (Energirådgivningen, 2018) was used in the calculations. A sensitivity analysis was made on the outcome of the LCA calculations. This was made due to the large number of variables included in the estimations and to show the results in various outcomes. The primary results were varied from 50 % – 150 % with gaps of 10 %.

3.7.2 LCC

The LCC was calculated using the estimated growth rate for electricity ranging from 2 % - 4 % and inflation rates from 1.5 % – 2.5 %. Life cycles are presented in 15, 25 and 50 years. The LCC was made to show the finical scope of expenses regarding additional costs related to reusing windows such as transport, refurbishing, retail price etc. The price for windows were chosen from the windows used in the LCA calculation and includes taxes. Price for electricity is set to 1 SEK/kWh, including taxes and grid-fees. Geometric gradient formula was used to calculate the LCC for 18 windows based on dimensions from the fictive house.

Geometric gradient (present worth): $P = A_1 \left[\frac{1-(1+g)^N(1+i)^{-N}}{i-g}\right]$

Geometric gradient (present worth): $P = A_1 \left[\frac{N}{1+i}\right] \; when \; i = g$

$P = \text{Present value}$
$A_1 = \text{Cost, year one}$
$i = \text{Inflation rate}$
$g = \text{Growth rate}$

A simple calculation was made to find the breakeven point for bricks. The calculation was made comparing cost of new bricks and extra labor needed to clean old bricks. Two types of new bricks were chosen using the lowest square meter price and the most expensive square meter prices available. To compensate for extra costs associated with selective demolition, extra transport and added labor for the bricklayer, the price for the new bricks were lowered with approximately 30 % of the retail price. The results were varied depending on different scenarios for labor cost.

Equation for calculating available time at different labor costs before reaching breakeven point;

$$(\frac{2}{3} \cdot \text{Price for new brick [SEK/m}^2\text{]})/\ (52\ \text{[Bricks/m}^2\text{]}\ \cdot \text{Labor cost [SEK/hour]}/\ 60\ \text{[Minutes per hour]}) = \text{Time gap [Minutes per brick]}$$

4 Results & Discussion

This section aims to reveal the most significant findings of the study.

4.1 Interviews

This phase consists of a series of structured and semi-structured interviews with different actors in the building sector. Nineteen interviews were conducted in total and the results are presented in sub-categories.

Background
When first presented with the subject, all respondents showed a clear interest and positive attitude towards the purpose of the interview. A clear majority of respondents interviewed had several years of experience within their respective field. A majority of interviewees described their company to be highly influential in their ability to choose materials and finds energy use and certifications to be very important. When addressing the importance of certifications, some respondents mentioned that certifications are an effective way of communicating technical requirements but could be a way of hiding flaws in energy and environmental performance factors of structures.

Reusable components and material properties
When asked to arrange different building components based on their reusability potential, the respondent's answers were spread. Brick is a component reoccurring within responses as a component with good reuse potential and tiles to have poor potential. Waste management specialist #1 answered that insulation is one of their biggest landfill fractions and that there seems to be no financial incentives in reusing insulation materials at the moment. The material properties are a recurring subject of interest for many actors. There is strong restraint against using materials without knowing precise specifications. Many respondents spoke about the difficulties of not knowing the properties for materials available in buildings today. Developer #1 says ”we need to know what we are placing into the buildings, i.e. fire and structural properties”. None of the manufacturers knew or had heard of the DfD concept. Both literature reviews, questionnaires and interviews show the need for preserving information on material properties to be a key factor in re-using components, especially regarding structural components. Project manager #1 answered that it could be reasonable not to reuse structural components in order to guarantee structural properties. Further elaborating that it is more beneficial to design components for easier disassembly, so it can be recycled and exchange parts that are damaged instead of demolishing.

Quantifying materials and components is preferably done in more than one source. Imprinting components with properties, such as U-values, load bearing properties, fire resistance, etc. is still thought to be the most secure way of preserving the information. In combination with the growing use for BIM (Building Information Model) in the building and management phase, the preservation of the information can be both secured and manageable. Still, it is critical in initial stages to communicate in all disciplines if there is to be any reuse of materials. Results show that the implementation of the idea must be within the earliest of stages in the building process. Many responses indicate the developer or the architect as the key actors in the feasibility of re-using components. Not only does the problems regarding information concern the principle idea of reuse, but also the spreading of experience.

”*Reuse is necessary for a sustainable future, but it requires building for future reuse and the majority of structures are not built for that*”

Actors in the building sector

When asked to arrange the most influential actors in terms of material and component choice, the answers indicated that architects and developers are seen as most influential and permit administrators as least. The manufacturers all agree that the contractor and developer is the most influential when choosing materials and components. ”The contractor will try to pick the cheapest material within the flexibility of the contract” . This issue is linked to the different contract forms used within the construction sector. There are well known guidelines and praxis in the Swedish construction sector, like ”general material and work descriptions” (AMA Hus), that are well implemented in contracts and construction related documents. This means that the process related to building and installing components are fairly standardized. When working with materials, finishes and components the rules and regulations differ between contract forms. This means that some contracts only allow the developer to demand functional requirements, giving the contractor the freedom of choosing material and finish. Municipality or government driven development projects are always excluded from specifying particular brands or manufacturers in contracts.

Incentives

When presented with the idea of lowered taxes for reused materials the respondents gave inconclusive answers. Some respondents indicate that financial incentives are the only way to make reuse possible on larger scale. Developer #1 stated that it might be a way to eliminate the elevated costs of working with reused materials and thought the effects would give positive reaction within the industry. On the contrary, the contractor #1 thought the approach might be wrong and the result might be neutral due to the labor intensity. The Swedish VAT includes materials sold as reused and is thereby attaching taxes to the materials twice.

Also, when presented with the idea of raising taxes on unsorted waste fractions the respondents thought the effects would be positive. It is thought to give the incentive for change and include everyone, but economical implementations are often perceived negatively. Contractor #1 believes that this is already on its way of becoming reality, but adds that this probably has greater effects in recycling rather than reuse. The investigator from the housing commission states that the idea of regulation waste management processes in the building sector with laws and regulations has been up for discussion but added that it is impossible to tell if such means are to be reality. The waste management specialist explains that the waste management sector is a competitive market. Making it difficult to assure quality in the delivered fractions of waste. ”We are not going to argue about small stuff with the customer, otherwise we risk losing clients”. The respondent further elaborated that there is a negative trend in the quality of delivered waste from the building sector. The trend can be explained by the economic upswing of the sector. ”When the sector is profitable, the sorting is neglected, this is completely based on the economy”. The respondent also adds that their biggest profit margins are on imported waste. The connection between the building sectors sorting rate and the economy gives the indication that waste is not expensive enough to be considered of importance in a construction project. Also, it is important to note the income generated by imported waste is high compared to the waste generated by the domestic market. Leading to the notion that less generated domestic waste could allow for more space in the incineration plant, potentially increasing imported waste and raising profits as well as lowering environmental impact. Also, the waste industry is an open market and is subjected to competition, making prices a critical issue.

Rules and regulations

When presented with the idea that the building regulations would make changes with the purpose of enhancing reuse, the respondents thought the industry’s perception would be negative. They agree on the substantial impact a properly formulated regulation would have but present the reality that reinforcing measures often are perceived negatively. The inspector from the housing commission states that ”small businesses will have a challenging time to comply witch such restrictions”. The difficulty of implementing such changes are raised by all respondents. ”It is hard to know the repercussions of such a change, but it would certainly make some noise in the industry”. The environmental specialist stated that they have ongoing projects to present suggestions to the Swedish housing commission regarding the implantation of reuse.

Barriers

When asked about the biggest problems and downsides of reusing components the respondents replied that ”availability”, ”quality” and ”quality assurance” are one of the mayor aspects. Developer #1 ”The building process is a lengthy and difficult to change, we have to work with extending the lifespan of components”. Project

manager #2 says, ”the link to demolition is weak, somebody needs to show the way”.
A clear majority of respondents indicate that there is a missing link in the process. Many say that there is a need for an actor that can handle the logistics and take responsibility for insecurities regarding warranties and quality of reusable components. None of the respondents wants to oversee storage or assembling a hub for reuse.

”*We are not able to handle the logistics, somebody else must take responsibility over handling, renovation and refurbishments. Solutions that are present today are in too small quantities and too late in the building process*”.

”*It is hard to find financial value and profitability in reuse on a larger scale. It is difficult to get volume and quality in products and deliver on time*”

Several respondents say that they have addressed the question of reusing products in their projects. Key issues related to the subject is linked to both cost and logistics and explains that there is a risk for materials being stored to just ends up in storage, without ever being used. Developer #2 explains that it is a time-consuming process and is directly linked to the cost of the project. Unfortunately, there is often a strict deadline when working in the construction sector. Projects start quite fast and there is little time to evaluate or even consider reuse. It is agreed by the respondents that reuse is to be incorporated very early at the project stage, possibly by the architect or developer. Developer #1 says they have addressed the possibility to reuse brick and stone for exterior use, but it is not integrated to their projects and only in terms of downcycling. Their main motivation for working towards a circular model is to minimize the ”use and waste” mentality and to take a holistic responsibility. The contractor has no experience in working with reuse as they find it difficult in terms of warranties, time aspects and deliverability. ”There is a pattern that need to change if this is going to work, and this costs money”. The respondent locates availability and quality as important aspects but finds it difficult to limit the issue to specific things, ”everything is expected to be new”. Both developer and contractor find quality to be one of the most important factor when choosing a material or component. Inconsistency in quality appears to be one of the major contributors in restraining reuse of materials in the commercial sector. Delivering refurbished components with the same quality and consistency as new products requires for the components to be designed with the intent of making minor restorations. Also, this puts more emphasis on the availability of skilled labor.

”*We are not a logistics company, it is often more efficient and financially profitable to use a new material*”

Availability seems to be another major concern for some of the interviewed actors. Usually large volumes of material are required and mixing new with old is not seen as a reasonable option. Project manager #1 explains that the quantities of components required for a new building, even small projects, can never be met by the availability of reused components. Further explaining that there is a desire to build with highly energy efficient components, eliminating reused windows since they may be technically depleted. There is little incentive to try re-using materials because of the low volumes and small profit margins according to the investigator from the housing commission. It is important to note that even new builds generate usable components and materials. Usually estimates are made with margins due to the probability of damaging goods in transport. Environmental specialist #1 explains that the bottom board in a gypsum pallet is often discarded because of scratches and inconsistencies. If one board in a pallet is damaged, the whole pallet is often discarded by the manufacturer. Research indicates that dismantling costs could be up to 30 % higher compared conventional demolition (Härle, et al., 1995) (Dantata, et al., 2005). This is mainly linked to low fraction costs but could also be lowered with experience of dismantling buildings. Nonetheless, it seems that the industry is profitable while using new materials and the reuse of materials is costly in comparison.

None of the participating manufacturers worked or had worked with reuse in any form. One manufacturer reply that they investigated the possibility of using reused brick in their products but concluded that the profits where not motivational. Another respondent said that their product had not been on the market to be able to investigate the reuse possibilities. This indicates that there could be an interest of not reusing materials or components. The possibility of reusing was perceived as very distant from most participating manufacturers.

When manufacturers were asked about the pros and cons of working with circular economy, two out of five respondents answered that ”it would halt the development process” and ”it would reduce sales”. One respondent answered that ”it would create a better environment”. It is difficult to know if the lack of incitement to get involved in the process of reusing materials and components are due to financial restrictions or lack of understanding in the process of reusing. Manufacturers generally spoke about the difficulties in regard to the technical aspects, such as air-tightness, load bearing capacity etc. which indicates that there could be a general interest in keeping the process linear. The manufacturers are thought to be one of the actors most impacted by a shift to a circular economy model.

Opportunities

A majority of the respondents answered that a combination of government tax reductions and motivational aspects would have the desired effect on pushing the circular models forward. ”Many companies have environmental ambitions, but it is about creating spirals that give and effect, there are financial aspects in everything”.

4.2 Surveys

4.2.1 Building regulations

The Swedish building code was addressed in terms of flexibility and implementation of rules and regulations. The results show that a clear majority of respondents are interpreting the law as intended. Meaning, the reuse of windows is not limited by the high U-value generally associated with old windows. Although, the results indicate a possible problem when addressing the ”historic value” of buildings. It seems as ”historic value” is only linked to the whole façade or building and does not involve component level. Meaning that a façade could be seen as historically valuable but only windows do not.

4.2.2 Survey results

The most significant findings from the survey is presented in this section. The survey was distributed to all 290 municipalities in Sweden. 75 responses were registered and after processing, 60 responses remained. 15 responses were removed due to conflicting and unserious answers. Among the respondents, approximately 77 % were building inspectors and around 83 % had one or more years of experience in the field. The survey can be found in appendix 7.2

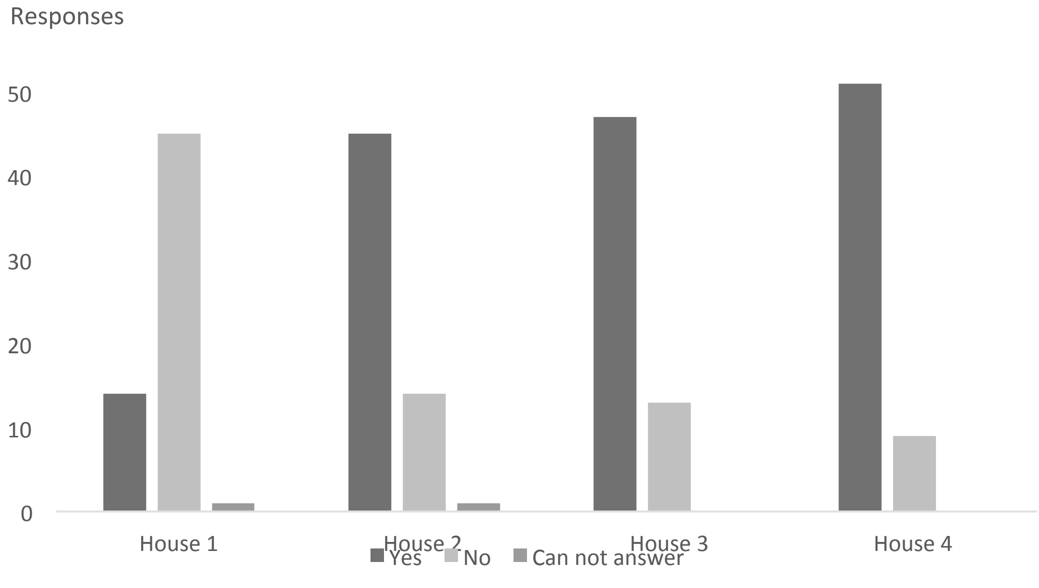

Figure 6 – Results to question 2.1-2.4 “Based on given parameters. Would you give House 1/2/3/4 a starting clearance?”. Expected answer for house 1; 'No'. Expected answer for house 2-4; 'Yes'.

As showed in figure 6, a majority answered ”No”. Some of the ”Yes” answers could not be explained, but most of them motivated their answer. Question 2.1 was used as a way of evaluating if the respondents had read and understood the energy calculations.

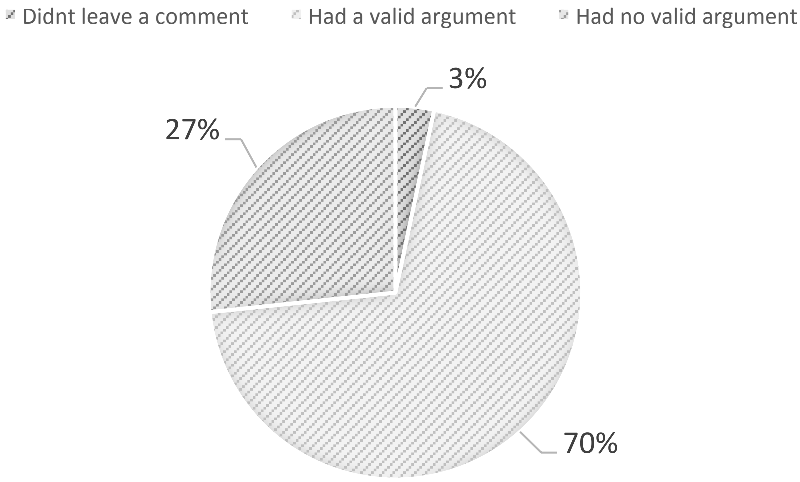

Figure 7 - Survey results. Motivations to question 2.1-2.4. A valid comment is for example; ”The requirements according to the energy calculations are not met in ” House 1” but are met in ” House 2-4”. A non-valid argument is; ”My task is to review the energy calculations, not to do them”.

Figure 7 indicates that a clear majority of respondents understand the energy calculations and are implementing the rules and regulations as intended. Resulting in the fact that using windows with U-values of $2.0\ \mathrm{W/(m^2 \cdot K)}$ is acceptable if figures for ”installed effect”, ”average U-value” and ”EP_{pet}” is within the limits.

4.3 **Calculations**

4.3.1 LCA for windows

The three tables (6, 7 and 8) show how the emissions due to manufacturing of windows are affected by various sources. A sensitivity analysis was made, using ”extra embodied energy” as the parameter. This is the energy needed to produce 18 windows with the size of 1.2 m · 1.2 m compared to the loss in energy due to poor energy performance of the reused windows. The value is varied to show how the embodied energy affects the overall viability of the process. The window components were summarized and compiled from twelve materials to five in order to simplify the LCA calculations. This resulted in a total of 101 kg CO_2 eq. (see table 5). Primary heat source is set to electricity. This is seen as one of the less environmentally friendly options but allows for a simplified comparison. Various sources for ”emissions/kWh” were included in the sensitivity analysis. The sources are indicators for Sweden and range from the lowest emissions ”(kg CO_2 eq.)/kWh” to the highest. This is due to the vast variation between sources. The sensitivity analysis was varied from 50 % - 150 % based on the initial value of 101 kg CO_2 eq. for the windows. Tables 6-8 show the sensitivity analysis in three intervals (100 %, 70 % and 130 %). 100 % represents the total impact from the LCA, that is varied with 30 % increase and decrease.

Window components	Component materials	Weight /kg	Environmental impact from EPD/$kg_{CO_2\ eq.}$	Total impact/ $kg_{CO_2\ eq.}$
Glass	Float glass (4 mm)	**37.27**	**11.9/m^2**	**44.35**
Nails, screws & fittings	Steel	0.05		
TGI profile	Steel	0.45		
		0.51	**5 832.5/ton**	**2.65**
Frame	Pine wood	**9.04**	**- 699/m^3**	**- 11.70**
Aluminum profile	Aluminium	**1.92**	**16.19/kg**	**31.07**
Butyl	Polyisobutylene	0.05		
Desiccant	Zeolit	0.35		
Argon	Argon	0.05		
Paint	Poyuretan paint	0.30		
Plastic	PVC	0.10		
Rubber	EPDM	0.25		
Joints & sealants	Polysufid	0.02		
Edge sealing mass	Polysulfide	0.96		
		2.09	**4.2/kg**	**8.76**
Factory emission	Boundary A3			**26.0**
Total		**50.82**		**101.13**

Table 5 – Quantifying window components and materials using EPDs

It is apparent that the energy source has a significant impact on the LCA outcome. Looking at table 6, it is apparent that a reduction in total environmental impact by 30 % is for some cases not even viable for 15 years. Results indicate that even windows with poor energy performance are environmentally profitable when compared to the inbound energy of manufacturing a new high performing window. The reuse of older windows will certainly require refurbishment and additional materials, but results show that even a 30 % increase will not significantly impact the results. The environmental impact from electricity production affects the LCA results immensely. Sweden's electricity production has a low environmental impact compared to other European countries, hence small amounts of CO_2 eq. per kilowatt/hour. The outcome of the result would be very different if numbers from Denmark, Germany or Great Britain were to be used in LCA calculations (Electricity Map, 2018).

The value marked with grey in table 6 is the total amount of extra emitted CO_2 for the energy performance of "House 2". To get this value the "electricity environmental impact (25 g CO_2 eq.) " is multiplied by the "amount of years (50 years)" and the "extra electricity (2 106 kWh/year)". "Extra electricity" is the electricity difference of using new versus reused windows. When these values are higher than "extra embodied CO_2 (1 820 kg CO_2 eq.) the numbers are marked with red to indicate that the CO_2 for reused windows are higher than the embodied CO_2 of new windows. "Extra embodied CO_2" (kg CO_2 eq.), is the added environmental impact due to manufacturing new windows.

Table 6 – LCA for windows and sensitivity analysis on embodied CO_2, 100 %. (kg CO_2 eq.)

Data source of electricity environmental impact	Electricity environmental impact/(g co₂ eq/kwh)	Extra embodied co₂ /kg co₂ eq	House 2 Extra electricity 2 106 kWh/y with re-used windows			House 3 Extra electricity 1 889 kWh/y with re-used windows		
			15 Years	25 Years	50 Years	15 Years	25 Years	50 Years
Vattenfall	6,3	1 820	199	332	663	188	313	627
Energirådgivning	25	1 820	790	1 316	2 633	746	1 243	2 486
Electricitymap	54	1 820	1 706	2 843	5 686	1 611	2 685	5 370

Table 7 – LCA for windows and sensitivity analysis on embodied CO_2, 30 % reduction in embodied CO_2. (kg CO_2 eq.)

Data source of electricity environmental impact	Electricity environmental impact/(g co₂ eq/kwh)	Extra embodied co₂ /kg co₂ eq	House 2 Extra electricity 2 106 kWh/y with re-used windows			House 3 Extra electricity 1 889 kWh/y with re-used windows		
			15 Years	25 Years	50 Years	15 Years	25 Years	50 Years
Vattenfall	6,3	1 274	199	332	663	188	313	627
Energirådgivning	25	1 274	790	1 316	2 633	746	1 243	2 486
Electricitymap	54	1 274	1 706	2 843	5 686	1 611	2 685	5 370

Table 8 – LCA for windows and sensitivity analysis on embodied CO_2, 30 % increase in embodied CO_2. (kg CO_2 eq.)

Data source of electricity environmental impact	Electricity environmental impact/(g co₂ eq/kwh)	Extra embodied co₂ /kg co₂ eq	House 2 Extra electricity 2 106 kWh/y with re-used windows			House 3 Extra electricity 1 889 kWh/y with re-used windows		
			15 Years	25 Years	50 Years	15 Years	25 Years	50 Years
Vattenfall	6,3	2 366	199	332	663	188	313	627
Energirådgivning	25	2 366	790	1 316	2 633	746	1 243	2 486
Electricitymap	54	2 366	1 706	2 843	5 686	1 611	2 685	5 370

4.3.2 LCC for windows

The annual cost is the electricity needed to compensate for the energy losses through the windows. The energy price is estimated to be 1 SEK/kWh. 18 windows with the size of 1.2 m · 1.2 m have been used for the calculations. Results show that if the windows in this example is to be reused and estimated to last 25 years, the cost involving restoration, transport, dismantling and installation is financially feasible up to around 70 000 SEK - 100 000 SEK. Looking at table 9 it is indicated that there is approximately 4 000 SEK/window in transport, refurbishment and potential profit margins. Purely electrical heating systems is not commonly used in Sweden, usually more cost- and energy-effective hybrid systems are implemented, especially in areas where district heating is not available.

Table 9 and 10 present the same calculations but for different inflation and growth rates. Properties for "House 1-3" are presented in table 3. The houses marked "reuse" are thought to have the properties presented in table 3 and the unmarked houses are thought to be equipped with new windows, hence the investment cost. "Cost per year (SEK)" is the electricity cost for heating due to transmission losses. The houses are compared in terms of total cost. The numbers are marked with red when costs for reused windows are higher than new windows.

Table 9 - Inflation 2 %, growth rate electricity for 2 %

	Investment cost/SEK	Cost per year/SEK	Total cost/SEK		
			15 Years	25 Years	50 Years
House 1	153 018	8 073	274 113	354 843	556 668
House 2	153 018	6 903	256 563	325 593	498 168
House 3	153 018	6 201	246 033	308 043	463 068
House 1 (reuse)	-	10 062	150 930	251 550	503 100
House 2 (reuse)	-	9 009	135 135	225 225	450 450
House 3 (reuse)	-	8 190	122 850	204 750	409 500
Possible investment cost for reused windows					
”**House 1**” compared to ”**House 1 (reuse)**”			123 183	103 293	53 568
”**House 2**” compared to ”**House 2 (reuse)**”			121 428	100 368	47 718
”**House 3**” compared to ”**House 3 (reuse)**”			123 183	103 293	53 568

Table 10 - Inflation 2 %, growth rate electricity for 4 %

	Investment cost/SEK	Cost per year/SEK	Total cost/SEK		
			15 Years	25 Years	50 Years
House 1	153 018	8 073	294 963	415 353	841 622
House 2	153 018	6 903	280 532	388 683	771 618
House 3	153 018	6 201	267 565	364 717	708 710
House 1 (reuse)	-	10 062	185 868	343 512	901 689
House 2 (reuse)	-	9 009	166 417	307 563	807 326
House 3 (reuse)	-	8 190	151 288	279 603	733 933
Possible investment cost for reused windows					
”House 1” compared to **”House 1 (reuse)”**			109 094	71 840	- 60 066
”House 2” compared to **”House 2 (reuse)”**			114 115	81 120	- 35 708
”House 3” compared to **”House 3 (reuse)”**			116 277	85 114	- 25 223

4.3.3 Retail price

To evaluate the financial feasibility of reusing bricks, simple calculations on the relation between time spent cleaning one square meter brick and the variation in time depending on labor cost are presented in figure 8. This figure illustrates costs from two price points and the outcome in the sum of time that can be spent cleaning each brick before ”break-even” point. Prices are presented in square meters due to varying sizes from different manufacturers and do not include cost for mortar.

The marker in figure 8 shows that the time margin for cleaning bricks with an hourly rate/cost of 300 SEK/hour allows for approximately three minutes per brick. The values are based on m^2 prices for new brick of 1 195 SEK.

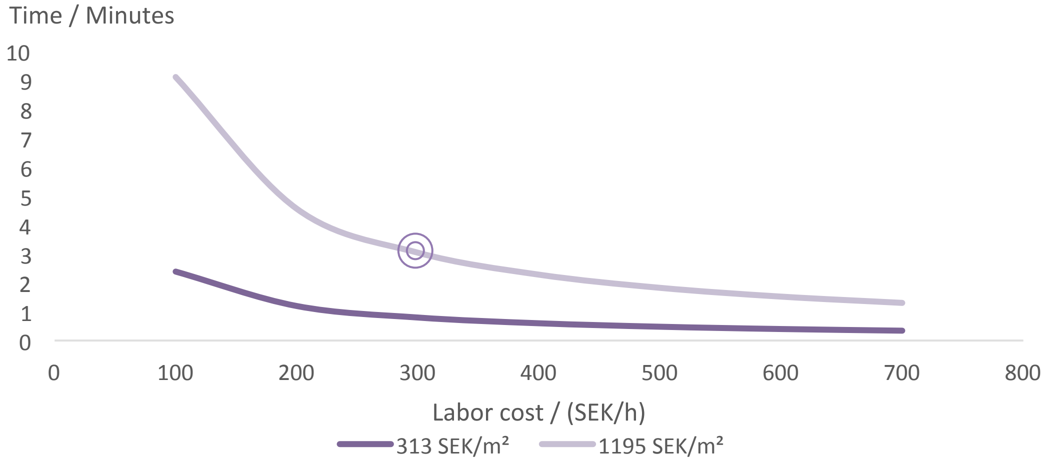

Figure 8 - Comparison of labor cost and retail price of bricks.

The results show that cheaper bricks are difficult to clean in terms of profitability. Several methods can be used when cleaning bricks and it is difficult to determine the minimum amount of time that would be physically manageable to clean each brick with current methods. Also, there are differences in mortar solidity. A lime-mortar is very easily brushed off while cement-mortars can sometimes be denser than the actual brick, causing it to break when separating.

5 Conclusion

It is apparent that current building materials and components, as well as building methods aren't adapted to further cycles of use. Downcycling is a potential way of using components otherwise discarded. Downgrading a component to a lower state of function is possibly an easier way of utilizing materials and components. It is indicated that the absence of dismantlable components could be due to lack of knowledge among manufacturers, since the DfD model was not recognized among any of the participating manufacturers. The financial incitements are also apparent, prolonging the usefulness of materials and components are going to affect profits and is therefore thought to be of little interest. Unless demanded from clients, the process of manufacturing is thought to remain unchanged.

Possible drivers for the circular model are seen as a combination of government tax reductions. Raised taxes on unsorted waste is thought to have positive impact on both reuse and recycling aspects. Unfortunately, the costs related to disposing waste are too inexpensive at the moment. Also, double taxation on products is seen as problematic. Taxes should be linked to the products first cycle, allowing for profitability in further cycles.

Compared to the construction rate, availability of reusable components is very low. Even small builds can not be provided by solely reused materials. Making it difficult to find profitability unless there is an added value to the reused component. Building with the option of structural flexibility, prolonging life of existing buildings and components is seen as superior option. But it is not an ”all or nothing” approach; reusing available stock is still more environmentally profitable than discarding or recycling. As seen from the LCA, it is apparent that the energy performance of windows will not compensate for the added inbound energy, making it unreasonable to change windows for pure energy savings. The level of reusable resources in Swedish energy production is high in comparison to some other countries, increasing the importance of investigating impacts in regard to inbound energy.

There are inconclusive results regarding the influences of different actors in the industry. Although, it is apparent that the reuse option must be presented at the earliest of stages, placing focus on contractors and architects. It seems that reuse has some effects on the ”architectural freedom” of designing. Intensive reuse is reasonably achieved by standardizing and ”modularizing” the components being used. Creating new obstacles in the creative process facing architects. On the contrary, a stricter modular building process would lead to faster building phase.

Since it is impossible to foresee the growth and inflation rates, no real conclusions can be made on finance. However, price on reused components does not appear to be a deciding factor. There seems to be a fundamental understanding of not implementing a wasteful mindset.

The desire for a ”key actor” or coordinator has been apparent on several occasions. There is a necessity for an actor to reassure quality, provide logistics and storage for reusable products. With seemingly slim profit margins, the probability is seen as low without further drivers. Instead, a non-profitable joint effort to lay the basis is seen as a reasonable step, possibly by major contractors and developers in Sweden.

5.1 Future research

Firstly, in order to further investigate the barriers and incentives of a circular economy in the building sector, one or several real cases should be studied. Bricks are potentially suitable case study components. Secondly, investigating how to design insulation with extended reusability potential is of importance regarding landfills. Further investigations on the feasibility and potential of a DfD process should be addressed to locate barriers and incentives. Finally, export possibilities of different components should be investigated to see how far various components can be transported regarding inbound energy. In addition, a method for linking cost in relation to footprint of extracting raw materials is necessary to gain a holistic picture of the LCC and LCA.

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7 Appendix

7.1 Survey formation

1. What municipality are you working for? (*Vilken kommun arbetar du på?*)
Response type; *Free text*

1.1 What employment title do you have? (*Vilken arbetstitel har du?*)
Response type; *Check question with 11 options*

1.2 How long have you been employed by the municipality under current employment title? (*Hur länge har du varit anställd på kommunen under aktuell arbetstitel?*)
Response type; *Check question with 4 options*

1.3 What is your highest education? (*Vilken är din högsta avslutade utbilding?*)
Response type; *Check question with 4 options*

Respondents were presented with the following tables (6-10) and accompanied paragraph text before continuing the survey;

Table 6 - Table 9.2a from BBR25, translated from Swedish.

	Energy performance expressed as primary energy number (EPpet) [kWh/m² and year]	**Installed power effect for heating (kW)**	**Average heat transfer coefficient (U_a) [W/m² K]**	**Average air leak at 50 Pa pressure difference (l / s m²)**
Housing				
Minor buildings	90	4,5 + 1,7 x (F_{geo} - 1)	0,4	According to Section 9:26
Minor buildings with smaller heated area than 50 m²	No requirement(s)	No requirment(s)	0,33	0,6
Apartment buildings	85	4,5 + 1,7 x (F_{geo} - 1)	0,4	According to Section 9:26
Non-residential premises				
Non-residential premises	80	4,5 + 1,7 x (F_{geo} - 1)	0,6	According to Section 9:26
Non-residential premises with smaller heated area than 50 m²	No requirement(s)	No requirment(s)	0,33	0,6

Table 7 - Table 9:92 from BBR25, translated from Swedish

	[W/m²K]
U_{roof}	0,13
U_{wall}	0,18
$U_{foundation}$	0,15
U_{window}	1,2
U_{door}	1,2

Text paragraph 1 -"General advice" from section 9:92 in BBR25, translated from Swedish

Windows: The windows are often of great importance for the building's perception and its cultural values. Reasons for departure from the requirement of the highest U value may be if the windows were manufactured specifically to satisfy the building's aesthetic values or cultural values. Original windows should only be replaced if windows can replace them as in terms of material, proportions, division and profiling is well adapted to the character of the house. Windows can also have such significant cultural values to they should not be replaced if there are no reasons. Instead, other measures should be taken to increase heat resistance.

Table 8 - Properties of all houses

Living area	117 m^2
Wall area	110 m^2
Roof area	117 m^2
Window area	26 m^2
WWR (Window-to-wall ratio)	24 %
Air leakage	0.6 $l/(s \cdot m^2)$
Heat recovery	80 %
DVUT (Dimensional winter outdoor temperature)	-9,8 °C
Average annual temperature	9 °C
The building is located in Lund. Thermal bridges make the rest of the U-values 25 % worse.	

Table 9 - Difference between houses

	Values that are soughed	House 1	House 2	House 3	House 4	Unit
Roof	0.13	0.13	0.0975	0.084	0.975	$W/(m^2 \cdot K)$
Wall	0.18	0.18	0.135	0.1	0.135	$W/(m^2 \cdot K)$
Foundation	0.15	0.15	0.1125	0.08	0.1125	$W/(m^2 \cdot K)$
Doors	1.2	1.2	0.9	0.65	0.9	$W/(m^2 \cdot K)$
Windows	1.2	2	2	2	1.5	$W/(m^2 \cdot K)$

Table 10 - Result from energy calculations

Results						
	Value that has to be met	House 1	House 2	House 3	House 4	Unit
Energy use	$90 \cdot 0.9 = 81$	86	77	70	69	kWh/m^2
Peak power	4 500 ($A_{temp} <$ 130 m^2)	3 812	3 385	2 960	3 049	W
Average U-value	0.4	0.37	0.33	0.29	0.28	kWh/m^2

2.1 Based on given parameters. Would you give ”House 1” a starting clearance? (*Baserat på givna parametrar. Hade du beviljat startbesked till Hus 1?*)
Response type; Check question with 3 options

2.2 Based on given parameters. Would you give ”House 2” a starting clearance? (*Baserat på givna parametrar. Hade du beviljat startbesked till Hus 2?*)
Response type; Check question with 3 options

2.3 Based on given parameters. Would you give ”House 3” a starting clearance? (*Baserat på givna parametrar. Hade du beviljat startbesked till Hus 3?*)
Response type; Check question with 3 options

2.4 Based on given parameters. Would you give ”House 4” a starting clearance? (*Baserat på givna parametrar. Hade du beviljat startbesked till Hus 4?*)
Response type; Check question with 3 options

2.5 Motivate your answer/answers to questions 2.1-2.4 (*Motivera gärna ditt/dina svar på frågan 2.1-2.4*)
Response type; Free text

3.1 The applicant explains that the choice of windows is based on economic saving. Had this changed your decision about starting clearance, if so what/which decisions? (*Den sökande förklarar att valet av fönster baseras på ekonomiska besparingar. Hade detta förändrar ditt svar angående startbesked, i så fall vilket/vilka beslut?*)
Response type; Check question with 5 options

3.2 The applicant explains that the choice of windows is based on aesthetic values. Had this changed your decision about starting clearance, if so what/which decisions? (*Den sökande förklarar att valet av fönster baseras på estetiska värden. Hade detta förändrar ditt svar angående startbesked, i så fall vilket/vilka beslut?*)
Response type; Check question with 5 options

3.3 The applicant explains that the choice of windows is based on preserving cultural values. Had this changed your decision about starting clearance, if so what/which decisions? (Den sökande förklarar att valet av fönster baseras på att

bevara kulturvärden. Hade detta förändrar ditt svar angående startbesked, i så fall vilket/vilka beslut?)
Response type; Check question with 5 options

3.4 The applicant explains that the choice of windows is based on environmental aspects (beneficial from a lifecycle perspective). Had this changed your decision about starting clearance, if so what/which decisions? (*Den sökande förklarar att valet av fönster baseras på att bevara kulturvärden. Hade detta förändrar ditt svar angående startbesked, i så fall vilket/vilka beslut?*)
Response type; Check question with 5 options

4.1 Is there anything you would like to add? (*Finns det något Ni vill tillägga?*)
Response type; Free text

7.2 **Questionnaire formation**

1.1 What employment title do you have? (Vilken arbetstitel har du?)
Response type; Check question with 11 options

1.2 How long have you been employed by the municipality under current employment title? (Hur länge har du varit anställd på kommunen under aktuell arbetstitel?)
Response type; Check question with 4 options

1.3 What is your highest education? (Vilken är din högsta avslutade utbilding?)
Response type; Check question with 4 options

2.1 What company / municipality / institution do you work for? (Vilket företag/kommun/instution arbetar du på?)
Response type; Free text

2.2 Which types of contracts are most common in your projects? (Vilken/vilka kontraktformer är mest förekommande i era projekt?)
Response type; Check question with 6 options

2.3 Choose how well you feel that the company / municipality / institution matches the following statements? (Välj hur väl du upplever att företaget/kommunen/instutionen passar in på följande påståenden?)
Following statement; Rethinking, environmentally conscious, sustainable and Leading.
Response type; Check question with 7 options in scale, from a lot/very much to not at all.

2.4 How important do you (as a company / municipality / institution) experience environmental certification? (Hur viktigt upplever ni (som företag/kommun/institution) att det är med miljöcertifiering?)
Response type; Check question with 10 options in scale, from a lot/very much to not at all.

2.5 How much do you feel (like company / municipality / institution) that you can influence the choice of materials and components? (Hur mycket upplever ni (som företag/kommun/instution) att ni kan påverka i val av material och komponenter?)
Response type; Check question with 10 options in scale, from a lot/very much to not at all.

2.6 Sort the following aspects when selecting product or building materials? (Rangordna följande aspekter vid val av produkt eller byggmaterial?)

Following aspects; Quality, price, guarantees, accessibility, manageability and environmental impact.
Response type; Check question with 6 options in scale, from most important to least important.

2.7 Which of the following components do you consider having good or poor reusability potential?
Following components; Exterior doors, windows, interior doors, radiators, steel beams, concrete beams, Wooden beams, Various fixed interior e.g. kitchen cabinets, bricks, Tiles/Clinker and roof tiles.
Response type; Check question with 3 options in scale, from good potential to bad potential.

2.8 Sort to what extent the following occupational categories are considered to affect reuse in the construction sector? (Rangordna i vilken utsträckning följande yrkeskategorier anses kunna påverka återbruk i byggsektorn?)
Following occupational categories; Architects, planners, building contractors, developers, building permits administrator, supply manager and project manager.
Response type; Check question with 7 options in scale, from highest affect to least affect.

2.9 When in the construction process, plans for reuse need to be lifted to make it a viable alternative? (När i byggprocessen behöver planer om återbruk lyftas för att det ska vara ett genomförbart alternativ?)
Response type; Check question with 7options.

3.1 Do you have any experience in reusing building components? (Har du/ni någon erfarenhet av att återbruka byggkomponenter?)
Response type; Check question with 2 options in scale, Yes(sent to question 4.1) or no(sent to question 5.1).

4.1 What components / materials have you worked with?(Vilka komponenter/material har ni arbetat med?)
Following components; Exterior doors, windows, interior doors, radiators, steel beams, concrete beams, Wooden beams, Various fixed interior e.g. kitchen cabinets, bricks, Tiles/Clinker and roof tiles.
Response type; Check question.

4.2 Which / has been the biggest challenge of reusing the materials / components?
Response type; Free text

4.3 Choose at least one aspect that you consider to be the greatest benefit of reuse of products?

Following aspect; Price, accessibility, quality, guarantees, aesthetics and laws and regulations.
Response type; Check question.

4.4 Which / what were the contributing aspects of the recycling work? (Vilket/vilka var det bidragande aspekterna för arbetet med återbruk?)
Response type; Free text

5.1 Has there been a discussion about reusing of materials / components? (Har det varit aktuellt med återbruk av material/komponenter?)
Response type; Check question with 2 options in scale, Yes or no.

5.2 Choose the aspect (s) you consider to be the greatest challenge in the recycling of materials / components? (Välj den eller de aspekter som ni anser vara den sörsta utmaningen vid återbruk av material/komponenter?)
Following aspect; Price, accessibility, quality, guarantees, aesthetics and laws and regulations.
Response type; Check question.

5.3 What are the pros and cons of your connection with the reusing process? (Vilka för- och nackdelar anser ni är kopplade till återbruksprocessen?)
Response type; Free text

6.1 Scenario 1; BBR (building regulation) introduces new rules for promoting reuse in the construction sector. How do you think the industry reacts? (BBR inför nya regler för att främja återbruk i byggsektorn. Hur tror du branschen reagerar?)
Response type; Check question with 3 options. Positive, neutral or negative.

6.2 What do you think the effect will be? (Vad tror du effekten blir?)
Response type; Free text

6.3 Scenario 2; The tax is increased for waste, mainly mixed waste. How do you think the industry reacts? (Skatten höjs för avfall, främst blandat avfall. Hur tror du branschen reagerar?)
Response type; Check question with 3 options. Positive, neutral or negative.

6.4 What do you think the effect will be? (Vad tror du effekten blir?)
Response type; Free text

6.5 Scenario 3; Tax relief are introduced for the use of recycled materials. How do you think the industry reacts?
Response type; Check question with 3 options. Positive, neutral or negative.

6.6 What do you think the effect will be? (Vad tror du effekten blir?)

Response type; Free text

6.7 Do you think any of the scenarios can encourage reuse in the construction sector? (Tror du att någon av nämnda scenarion kan främja återbruk inom byggsektorn?)
Response type; Check question with 4 options. Yes, scenario 1. Yes, scenario 2. Yes, scenario 3 or none of them.

7.1 Is there anything you would like to add? (Finns det något Ni vill tillägga?)
Response type; Free text

7.3 LCA

Table 11 - LCA appendix

	Data source of electricity environmental impact	Electricity environmental impact/(g co_2 eq./kwh)	Extra embodied co_2 (kg co_2 eq.)	House 1 Extra electricity 1 889 kWh/y with re-used windows			House 2 Extra electricity 2 106 kWh/y with re-used windows			House 3 Extra electricity 1 889 kWh/y with re-used windows		
				15 Years	25 Years	50 Years	15 Years	25 Years	50 Years	15 Years	25 Years	50 Years
100%	Vattenfall	6,3	1 820	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	1 820	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	1 820	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
110%	Vattenfall	6,3	2 002	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	2 002	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	2 002	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
120%	Vattenfall	6,3	2 184	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	2 184	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	2 184	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
130%	Vattenfall	6,3	2 366	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	2 366	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	2 366	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
140%	Vattenfall	6,3	2 548	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	2 548	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	2 548	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
150%	Vattenfall	6,3	2 730	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	2 730	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	2 730	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
90%	Vattenfall	6,3	1 638	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	1 638	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	1 638	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
80%	Vattenfall	6,3	1 456	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	1 456	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	1 456	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
70%	Vattenfall	6,3	1 274	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	1 274	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	1 274	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
60%	Vattenfall	6,3	1 092	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	1 092	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	1 092	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370
50%	Vattenfall	6,3	910	188	313	627	199	332	663	188	313	627
	Energirådgivnir	25	910	746	1 243	2 486	790	1 316	2 633	746	1 243	2 486
	electricitymap	54	910	1 611	2 685	5 370	1 706	2 843	5 686	1 611	2 685	5 370

7.5 LCC

Table 12 - LCC appendix.

	Investment cost /SEK	Cost per year /SEK	15 years i=1,5% g=2%	25 years i=1,5% g=2%	50 years i=1,5% g=2%	15 years i=2% g=2%	25 years i=2% g=2%	50 years i=2% g=2%	15 years i=2,5% g=2%	25 years i=2,5% g=2%	50 years i=2,5% g=2%
House 1	153 018	8 073	278 997	368 292	611 705	274 113	354 843	556 668	269 493	342 530	510 235
House 2	153 018	6 903	260 739	337 093	545 229	256 563	325 593	498 168	252 613	315 065	458 464
House 3	153 018	6 201	249 784	318 373	505 343	246 033	308 043	463 068	242 484	298 585	427 402
House 1 re-use	-	10 062	157 017	268 312	571 697	150 930	251 550	503 100	145 172	236 203	445 226
House 2 re-use	-	9 009	140 585	240 233	511 868	135 135	225 225	450 450	129 980	211 485	398 633
House 3 re-use	-	8 190	127 804	218 394	465 335	122 850	204 750	409 500	118 163	192 259	362 394
Possible cost for the re-used windows											
House 1 compaird with house 1 re-use			121 980	99 980	40 008	123 183	103 293	53 568	124 321	106 327	65 008
House 2 compaird with house 2 re-use			120 154	96 860	33 360	121 428	100 368	47 718	122 633	103 580	59 831
House 3 compaird with house 3 re-use			121 980	99 980	40 008	123 183	103 293	53 568	124 321	106 327	65 008
	Investment cost /SEK	Cost per year /SEK	15 years i=1,5% g=3%	25 years i=1,5% g=3%	50 years i=1,5% g=3%	15 years i=2% g=3%	25 years i=2% g=3%	50 years i=2% g=3%	15 years i=2,5% g=3%	25 years i=2,5% g=3%	50 years i=2,5% g=3%
House 1	153 018	8 073	289 466	398 618	753 029	284 059	382 702	675 830	278 948	368 155	611 124
House 2	153 018	6 903	272 025	367 224	676 332	267 309	353 342	609 001	262 851	340 655	552 566
House 3	153 018	6 201	259 922	345 440	623 113	255 686	332 970	562 630	251 681	321 574	511 934
House 1 re-use	-	10 062	173 467	312 232	762 796	166 593	291 998	664 653	160 095	273 505	582 392
House 2 re-use	-	9 009	155 314	279 556	682 969	149 159	261 440	595 096	143 341	244 883	521 444
House 3 re-use	-	8 190	141 194	254 142	620 881	135 599	237 673	540 997	130 310	222 620	474 040
Possible cost for the re-used windows											
House 1 compaird with house 1 re-use			115 999	86 386	-9 768	117 466	90 704	11 177	118 853	94 650	28 732
House 2 compaird with house 2 re-use			116 711	87 667	-6 637	118 150	91 902	13 905	119 510	95 773	31 122
House 3 compaird with house 3 re-use			118 728	91 298	2 233	120 087	95 297	21 633	121 371	98 953	37 894
	Investment cost /SEK	Cost per year /SEK	15 years i=1,5% g=4%	25 years i=1,5% g=4%	50 years i=1,5% g=4%	15 years i=2% g=4%	25 years i=2% g=4%	50 years i=2% g=4%	15 years i=2,5% g=4%	25 years i=2,5% g=4%	50 years i=2,5% g=4%
House 1	153 018	8 073	300 950	434 217	950 868	294 963	415 353	841 622	289 306	398 138	750 603
House 2	153 018	6 903	285 911	405 631	869 758	280 532	388 683	771 618	275 451	373 219	689 852
House 3	153 018	6 201	272 396	379 941	796 869	267 565	364 717	708 710	263 000	350 826	635 258
House 1 re-use	-	10 062	193 708	368 215	1 044 740	185 868	343 512	901 689	178 461	320 971	782 503
House 2 re-use	-	9 009	173 437	329 681	935 406	166 417	307 563	807 326	159 785	287 381	700 614
House 3 re-use	-	8 190	157 670	299 710	850 369	151 288	279 603	733 933	145 259	261 255	636 921
Possible cost for the re-used windows											
House 1 compaird with house 1 re-use			107 241	66 003	-93 872	109 094	71 840	-60 066	110 845	77 167	-31 901
House 2 compaird with house 2 re-use			112 474	75 950	-65 648	114 115	81 120	-35 708	115 666	85 838	-10 762
House 3 compaird with house 3 re-use			114 727	80 231	-53 500	116 277	85 114	-25 223	117 741	89 570	-1 663

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