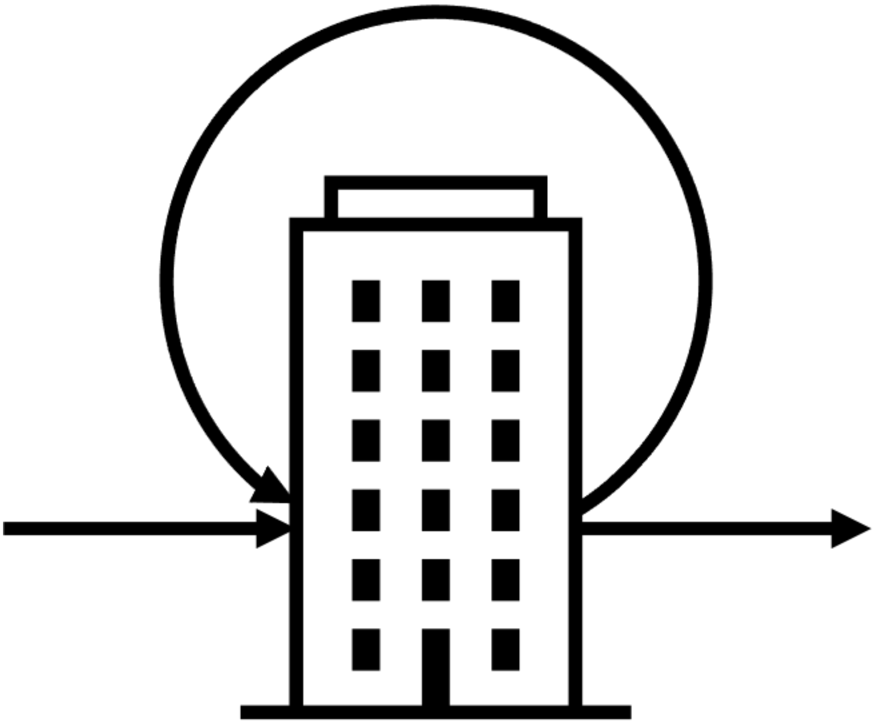

LCA framework for assessing the effects of reuse on climate impacts

Modelling the use- and reuse activities of the product life cycle to compare potential emissions between linear and circular product flows in the construction industry

Master's thesis in Industrial Ecology

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Cover: Illustrating circular material sourcing in the construction industry.

Gothenburg, Sweden 2021

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Abstract

The construction industry is one of the industries in the world that contributes with the most greenhouse gas emissions. To reduce emissions and increase the circularity of the industry, the CCBuild platform is being developed as a collaboration hub for stakeholders in the market to meet and share knowledge. The platform offers a tool for calculating the potential reduction in emissions if products in the building are reused instead of bought new. However, the current tool does not take the entire life cycle into account, since it excludes processes linked to the use- and reuse phases of the products life cycle. Effects on use phase energy consumption, as well as emissions connected to enabling reuse, are expected to contribute to the difference in emissions from the two options.

This thesis uses an inductive method to analyze how to include processes from the use- and reuse phase, without compromising the user-friendliness of the tool. This has been done through two case studies where the difference in climate impact between reusing and buying a new window as well as to reuse and buy a new dishwasher has been assessed. The findings and experiences from the case studies have then been used to develop a guide for how comparative attributional life cycle assessments can be carried out in order to generate results facilitating decision making. The guideline consists of a conceptual flow chart, for modelling the life cycle flow of an arbitrary product; a description of calculation procedures, and a discussion on the relevance of certain processes that should be included; and suggestions on which parameters that can be based on assumptions and be included in the tool's background data and which need to be specifically inventoried and entered into the system by the user. The parameters are chosen to represent the products included in the case studies, however it is expected that the studied parameters can be used to produce calculations for products of yet other product types. The results produced with the model represents an estimation of the total net emissions from reusing a product instead of buying a new one.

Keywords: Life cycle assessment, LCA, Reuse, Construction, CCBuild, EN 15978.

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Eva Kultje & Joel Löfving, Gothenburg, May 2021

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List of Abbreviations

LCA	Life cycle assessment
EPD	Environmental Product Declaration
ps	Place setting
Boverket	National Board of Housing, Building and Planning
CE	Circular Economy
GWP	Global Warming Potential
CO_2-eq	Carbon dioxide equivalents
IVL	The Swedish Environmental Research Institute

1

Introduction

1.1 Background

In 2018, 12 million tons of waste was generated in the Swedish construction industry [1]. Large parts of the materials and products used in construction flow linearly [2], meaning that old units are left for waste treatment after a renovation or deconstruction and replaced by new units. These are often made from virgin material, contributing to the construction industry's position as one of the biggest contributors to resource depletion, waste generation and pollution worldwide [3][4][5].

The construction industry's transition to a circular economy business model, which could lower it's burden on the the environment, is facing several challenges [6][7]. Gerhardsson et. al. [8] suggests that addressing some of these problems could result in synergistic effects efficiently improving the conditions favouring a more circular market.

To help stakeholders in the construction industry address problems associated with linear material flows, a platform for industry collaboration called CCBuild is being developed by IVL Swedish Environmental Research Institute. The purpose of the platform is to promote reuse in the construction industry in several ways; it serves as a knowledge sharing- and collaboration hub, and involves actors to create new market functions needed for the reuse to be successful.

One of the actions proposed by Gerhardsson et. al. [8], is to provide tools to increase the knowledge for decision makers in the industry. According to Ortiz et. al. [9], life cycle assessment (LCA) is a useful tool for this purpose, clarifying the consequences of certain actions to stakeholders. Furthermore, Oregi et. al. [10], says that even simplified LCA methodologies can provide results sufficient to use as basis for making decisions.

One part of the CCBuild platform is aimed at developing an inventory application, where property owners can input the products included in their building and print an estimation of the amount of greenhouse gas emissions that would be avoided if a certain (or all) products were to be reused instead of replaced by new ones. This information is calculated using LCA, and could be useful in order to lower greenhouse gas (GHG) emissions, e.g. when re-adapting the space for a new tenant or deciding how to go through with a renovation project.

However, the model for what is included in the calculations used in the tool today does not consider the entire life cycle perspective. Currently, the model accounts for emissions from producing a new product and discarding the old one [11], compared to only transporting the existing product to a storage facility. This gives an indication of potentials to avoid climate impacts, but does not convey the whole picture. We will in this study look into how processes in the use phase, as well as the activities connected to enabling reusing a product, may affect the results. Including this in the calculations might prove to be important in order to make the results trustworthy as a basis for decision making in different projects. At the same time, including too much detail in the calculations might not add extra value, as long as the most important flows are considered [10].

Including the entire life cycle perspective in the assessments does open up for many uncertainties. How the product is *actually* used during it's life time can never be known with complete certainty in advance, and thus a discussion on what assumptions can be made with regards to that is important. Discerning differences in e.g. energy consumption between two products with similar or equal modes of use can be hard, if it is even possible, to the person taking inventory of the building. Especially considering that taking inventory is already labour intensive, and companies are interested in getting it done with little effort. Even if the information proves easy to find for some product groups, entering it into the system should be easy as well, and being able to perform robust calculations with only a few values would thus be beneficial.

What kind of processes that are included in the reuse phase will also vary from case to case. Whether a product needs reconditioning or repair affects the impact of reusing a product. The distance to and characteristics of a storage facility, if any is used, will influence the impact as well. Mapping these processes out and discussing how to handle their environmental loads is important, in order to be able to make good modelling choices.

A description of how to efficiently estimate the total net effect on life cycle emissions from reusing a building material or -product instead of installing a new one, has not been identified in the literature. Analyses describing reuse activities' effects on the potential net emissions saving for this type of products have neither been described explicitly. This gives a valid reason to conduct such analyses in this thesis.

The contribution of this report to the knowledge base is thus a discussion and suggestion, or guideline, on how LCA can be used to model comparisons between the estimated life cycle emissions from sourcing products linearly and circularly. The guideline should hopefully be able to produce results reliable enough for use in decision making, when calculations are being conducted on an arbitrary product of a certain category with a small amount of product specific information available.

1.2 CCBuild

CCBuild is a platform developed by IVL with partners from different companies all over the Swedish construction industry. The platform includes cooperation and networks, a knowledge hub and digital services that aims at supporting and developing circular construction. As can be read on the CCBuild website;

> The vision for CCBuild is to create conditions for reuse of construction products on an industrial scale and contribute to change at a system level towards circular material flows. This enables a more resource- and climate efficient societal development where waste becomes resources and extraction of virgin assets is held back. [Translated from Swedish] [12].

Besides the inventory app mentioned in section 1.1, the digital services offered in the CCBuild platform include a marketplace for reused products, a product library for inventory, and a value analysis tool. It is in the value analysis tool that the user can print an assessment of how much emissions of CO_2-equivalents would be avoided if a certain (or all) products, that were inventoried using the inventory application, were to be reused instead of replaced by new ones.

According to representatives from IVL who work with developing the CCBuild platform it is of high importance that the tools are easy to use and that entering data can be done without a lot of effort for the user. The representatives from IVL argues that the CCBuild users typically do not have a lot of experience with LCA, and may therefore not have knowledge of what parameters that are important to inventory. It is also argued that the inventory process need to be as quick and easy as possible, since the person in charge of the inventory process usually are under quite tight time constraints. This means that the parameters asked for should be few, and easy to identify for the specific inventoried product.

The CCBuild inventory tool is primarily directed at compiling information on individual products and components built into a building. In order to drawing conclusions on what products are interesting to include in the inventory, and furthermore in the reuse assessment, inventory data from a specific building included on the CCBuild platform has been studied. This specific building had been inventoried using the inventory application.

There are 5825 individual product units included in the studied inventory. These are sorted into the 13 categories, 88 subcategories and some 200 product types available in the CCBuild tool[1], according to the tree structure shown in figure 1.1. An example of a category is ”Doors”, an example of a subcategory is ”Exterior doors” and an example of a product type is ”Exterior door with glass”. However, the distribution of products among the different product types is uneven in the studied project. For instance is 2245 products sorted into the product type ”Other electrical products”.

---

[1] This number of categories, subcategories and product types were included at the time of downloading the report. The system has since been updated to include more detailed groupings.

1237 products are furthermore entered into the category named ”Other”, without an assigned product type or subcategory. In total almost two thirds of the products can be said to have been categorized with high uncertainty in the system.

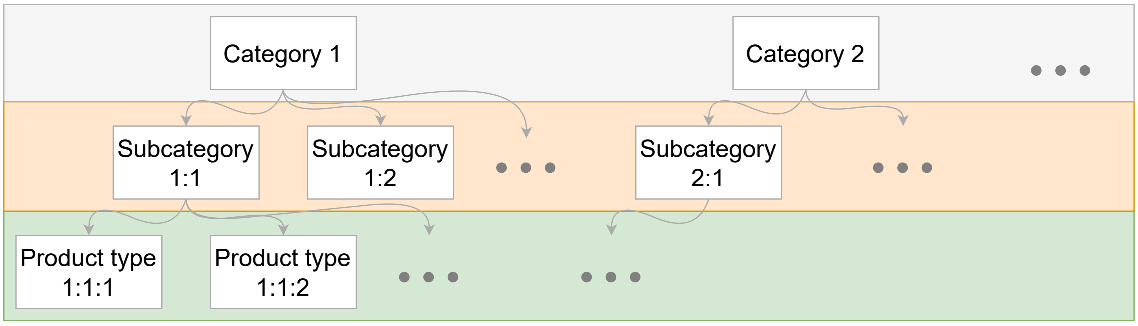


Figure 1.1: Schematic illustration of how products are sorted in the CCBuild tool

1.3 Aim

The aim of this thesis is to analyse how emissions from the use- and reuse phases can be taken into account when calculating the difference in environmental impact between reusing a product and buying a new one, using an attributional life cycle assessment.. These will be based on a small amount of product specific information, requiring many parameter values to be based on assumptions. The aim also includes presenting a guideline for how such calculations could be conducted for different product types, making the results reproducible for more products embedded in a building.

1.4 Limitations

The thesis will be limited to only analyse how emissions from the use- and reuse phases can be taken into account for two categorically different products groups. This is in order to get a deeper understanding of how their respective characteristics should be handled in an assessment. This means that other parts of the product life cycle will be studied with a lower amount of detail.

How the model should be integrated into the tool will not be discussed.

LCA specific delimitations are presented in section 3.2.1.

2

Theory

This chapter provides a theoretical foundation for the thesis. It begins with a description of the differences between linear and circular material systems, to provide an understanding in how they work and what their implications are. This is followed by a brief presentation of the relevant parts of the CCBuild platform (within which this project is conducted), as well as a short narrative about the theory behind LCA. Literature findings are then presented regarding how LCA can be applied to the building industry in general and this type of assessments in particular. This includes perspectives on including reuse activities in LCA, how these problems can be modeled, and how relevant legislative factors come into play. The section is concluded by formulating the two research questions for the thesis.

2.1 Linearity vs. circularity

The concepts of linear- and circular resource flows will be presented in this section, as well as a description of their relation to one another. This section is meant to be used as a background since the material systems studied in this report are based on these concepts.

2.1.1 Linearity

The linear model for production and consumption employed in the industrial system across the world is based on extracting resources, processing and combining them into products, and then using or consuming them before discarding them [13]. Merli et. al. [14] describes the linear system as a pattern of ”take-make-dispose”, and it is considered the defining characteristic of the material system supplying the world with goods today [15]. All the while, materials and substances on Earth are limited; be it either by their absolute abundance, or by constraints posed by e.g. economical or technical feasibility of extraction of raw materials [16]. When resources are not regenerated as fast as they are consumed, value is lost across the entire supply chain, and more inputs are required to sustain the flow of products through society. This increases the stress on nature further, resulting in negative environmental externalities often not represented by the price of the good [17].

2.1.2 Circularity

Circularity, or rather the Circular Economy (CE) as a concept has developed alongside other schemes (e.g. Industrial Ecology) to address the problems of linear material flows [7]. It's definition is non-static, hosting a range of different methods and perspectives whose purpose is to promote an industrial system where resources is kept in circulation, maintaining their value. These include e.g. eco-design, industrial symbiosis, measures addressing resource- and energy efficiency and the waste-hierarchy, all examples of addressing the issues on different system levels and in different parts of the value chain [18]. The goal is for a product or material to be possible to use as an input to another function, once it can no longer serve it's purpose in it's current function, creating a loop in society [14].

The waste hierarchy has been a driving concept in the development of the CE in the EU, embedding in to law the action prioritization among the three R's [19]: first *reducing* the amount of materials consumed, then *reusing* as much as possible of what materials are already embedded in society, and thirdly *recycling* as much as possible of what is left. In the construction industry the recycling rates have gone up in recent years; as an example, however, in the Netherlands only 3-4% of the material in new buildings are from a secondary source, even though 95% of all waste from the construction industry is recycled [20]. These activities are primarily performed in an open-loop, down-cycling manner, which according to Rose and Stegmann [4], is better described as ”delayed disposal” than recirculating materials back into society. This type of end-of-pipe solutions, neglecting to retain the value of the goods flowing through, is one of the many obstacles to the transition to a circular economy [3]. Even if CE is a widely recognized concept, the development is slow [13], the current rate of circularity in the world currently at 9,1% according to the organization Circle Economy [21].

2.2 Life Cycle Assessment

Life cycle assessment (LCA) is a method for evaluating the environmental impacts of a product or service over it's life time. The assessment is done by accounting for the emissions and resource consumption connected to processes throughout the lifetime of the studied object [22]. What processes to include in the different life cycle phases differ according to the object of study, the chosen boundaries of the system, the LCA methodology used and the level of detail employed in the study.

The overarching methodological steps in an LCA are goal and scope definition, inventory analysis, impact assessment and interpretation. The course of the study should not be linear, however; it is commonly recommended (and also required by the LCA standard ISO 14040 [23]) that an LCA practitioner move between these steps in an iterative manner, revisiting and updating with new insights and letting the respective results influence each other. A graphical representation of the workflow, based on ISO 14040 [23], can be seen in figure 2.1.

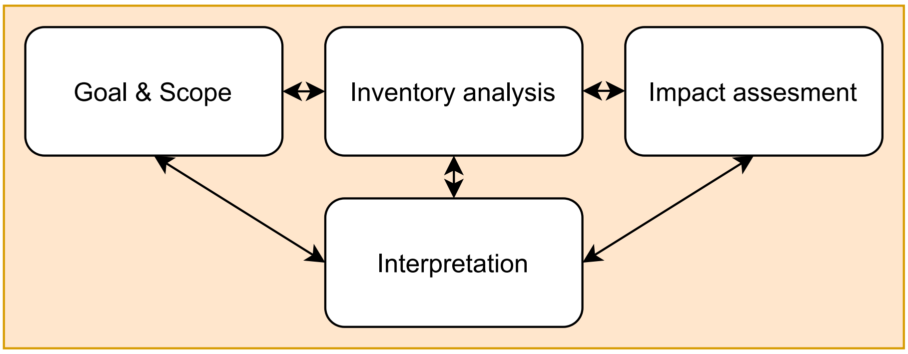


Figure 2.1: Graphical representation of the workflow, based on ISO 14040.

To produce a coherent study, one particular methodological choice that needs to be made is whether to use attributional or consequential modelling. Attributional LCA, is a methodology for assessing the total life cycle impacts of a product or service [22]. This is an additive modelling scheme, meaning that several attributional LCA's can be combined to calculate the environmental impacts of a larger system, or the differences between two systems can be compared. Consequential LCA on the other hand is a methodology for assessing the environmental impacts that occur as a consequence of the differences in demand brought on by a certain choice [22]. This puts high demands on case specific data, and makes the assesments hard to compare with other study results.

2.3 LCA regulations in the construction industry

Regarding how LCA is used within the Swedish construction industry today, two aspects are relevant to consider. These are the European standard for valuing the environmental performance of buildings, EN 15978, and the upcoming act on climate declarations for new buildings proposed by the Swedish government. These will be presented in the following subsections.

2.3.1 EN 15978 - Assessment of environmental performance of buildings

The standard EN 15978 describes how the environmental performance of buildings should be assessed [24]. This includes regulating how the LCA methodology should be applied. Since the resulting guideline from this thesis is aimed to be used for products within a building, adhering to EN 15978 is of interest in order to be able to use the results in the assessment of the environmental performance of an entire building.

The standard divides the different activities of the life cycle into different modules, named A, B, C and D. Module A-C describes different stages of the life cycle of a building, and contain several processes. Each process groups one or more activities with an environmental burden [24]. The processes are listed in tables 2.1 - 2.3. Module D describes environmental effects that should rather be connected to a different building, and will not be considered in this study.

Module A contains five processes (A1-A5) shown in table 2.1. These constitute the entire procedure of producing and transporting goods to be used in the building, and then constructing the building and installing the building materials.

Table 2.1: Processes included in module A, according to EN 15978

A1	Raw material extraction
A2	Transport to manufacturing
A3	Manufacturing
A4	Transport to building
A5	Construction and installation

Module B contains seven processes (B1-B7) shown in table 2.2. These constitute the entire use phase in the building.

Table 2.2: Processes included in module B, according to EN 15978

B1	Use
B2	Maintenance
B3	Repair
B4	Replacement
B5	Refurbishment
B6	Energy consumption during use
B7	Water consumption during use

Module C contains four processes (C1-C4) shown in table 2.3. These constitute the entire procedure of transporting the goods away from the building and handling and disposing of the waste.

Table 2.3: Processes included in module C, according to EN 15978

C1	Disassembly, deconstruction
C2	Transport
C3	Handling of residual waste
C4	Disposal

2.3.2 Climate declarations

A new act, implying that the environmental performance of all new buildings must be published in a climate declaration, has been proposed by the Swedish government. It is currently on track to be introduced on the 1st of January 2022 [25]. As of now the proposed declaration is limited to only require accounting for the production phase, represented by module A in the EN 15978 standard. The aim of the declarations is to increase the knowledge, and in turn lower the climate impact from constructing new buildings.

Boverket is the agency in charge of implementing the climate declarations. One action they will take is to provide an open database with data that can be used for calculating the climate impact of a building [26]. This database is, as of writing this thesis, open for a test period and the full version is to be launched in June of 2021.

Boverket has also been commissioned by the Swedish government to make a plan for the future development of the climate declaration [25]. As previously mentioned the current proposal only requires accounting for the climate impact from the production phase of a building. However, Boverket proposes that by 2027, additional processes from module B and C should be accounted for [25]. When accounting for the climate impact from module B, the reference time frame that will be used is 50 years. Boverket [25] states that the purpose of including these additional modules is to cover the entire life cycle of a building.

2.4 Reuse of building materials from a life cycle perspective

2.4.1 Including reuse in the building product life cycle

The LCA methodology is inherently based on products flowing from a ”cradle”, and eventually ending up in a ”grave”. Circular processes, looping materials back into earlier stages of the life cycle, are however getting more common in LCAs with time [22]. These circular processes can be modeled in two different ways, either as loops where materials circle back into previous processes which can be described as closed loop processes, or as consecutive use phases which can be described as open loop processes.

Circular process are also often connecting back from processes late in the life cycle, in the form of *recycling* of raw materials etc. Recycling is in general a more studied subject than reuse, in the construction industry [27]. The aim of the CCBuild platform is to increase the level of *reuse* to have circular processes higher up in the waste hierarchy (see section 2.1.2). Reuse of products within a building are, according to EN 15978, not considered a life cycle-loop, but rather a part of the use phase [28] [24] [29]. In EN 15978, module D is designated for environmental effects ”beyond the life cycle of the current building” and may be argued to account for reuse of specific products [24]. However, this module is based on consequential modelling of effects of e.g. avoiding the production of new products when reusing products elsewhere, and it is therefore incompatible with the other modules of the EN 15978-standard which are modelled attributionally.

With the aim of analysing how reusing a specific product within a building may affect the climate impact of the building across it’s entire life cycle, there is a need to account for emissions from reuse processes. How such calculations are to be conducted are not described explicitly by EN 15978.

2.4.2 Modelling perspectives

From the literature it has been found that reuse and recycling are commonly studied from the perspective of the entire building life cycle [29] [30] [31] [32] [33]. This type of assessment can be said to be conducted with a ”top-down”-approach, looking to the building as a larger system with many small parts. Each process in the building is then to be seen as a service-provider: an example would be an oven. As discussed in Vilches et. al. [30], the oven service during the lifetime of the building will be provided by a number of different ovens, and as such the impact for having an oven for the observed number of years will be calculated for the production, use and disposal of a certain number of generic ovens. These assessments are often done with process-based analysis, which present the studied system as a sequence of processes [34]. However it may also be done with input-output analysis, which uses economic transactions to analyse the environmental impact of a system and may, according to Cabeza et. al. [35], potentially capture more environmental damages. These studies give a good overview of the general flows through the building system enabling emissions calculations over the course of the life cycle.

The assessment provided by the CCBuild digital tool today gives results based on the potential environmental impact savings for each individual product included in the building. Adding them together, one could then be said to create a ”bottom-up” assessment of the building, producing a result based on the individual properties of the chosen products. This type of assessment would be inherently process-based. In literature, this has mostly been studied from a perspective on how to design products for deconstruction, making reuse possible in future buildings [36] [37]. With the CCBuild tool however, the aim is to clarify the potential savings of reusing products incorporated in the system today. If integrating the impacts from the use- and reuse phase, the CCBuild digital tool could thus provide holistic way of visualizing the specific product impact, in order to determine whether or not the product is appropriate to reuse, as a part of a larger system.

2.5 Research questions

After reviewing the literature available a knowledge gap has been identified. This gap is in regards to how people in the construction industry should easily calculate the total net emissions from reusing a building product instead of installing a new one, when taking the entire life cycle, including the use- and reuse phase, into account. In order to reach the aim of this thesis, and to fill the identified gap in the literature, the following overarching research question (with it’s following specified subordinated research questions) has been formulated:

- How can we formulate general recommendations on how to compare the total net emissions from reusing a product against replacing it for a new one?

- How should the activities connected to the use and reuse of a product be treated?
- How do we handle that there is little information available about the specific characteristics and history of the product currently in use, as well as the conditions for it's future use phase?
- How do we make the results reproducible for more products?

3

Methodology

To answer the research questions, an inductive research methodology was chosen. We decided to conduct two case studies, attempting to understand more about the effects of certain modelling choices by trying them in practice.

To do that, we first conducted a literature review in order to retrieve information regarding how LCA is used within the construction industry and how reuse is typically modelled in LCAs. Efforts were then put towards learning more about the conditions under which the CCBuild digital tool is used. This allowed to then formulate the problem to be studied, in the form of the research questions.

We then used the background studies as a foundation when performing the two case studies. The results from these were analysed by investigating the influence of different processes and parameters as well as by conducting sensitivity analyses. The experiences from these activities allowed us to draw conclusions and formulate our thoughts into a set of guidelines on how to handle the studied problem. The different steps of this process is described further in the following sections.

These steps, and how they connect, are shown in figure 3.1.

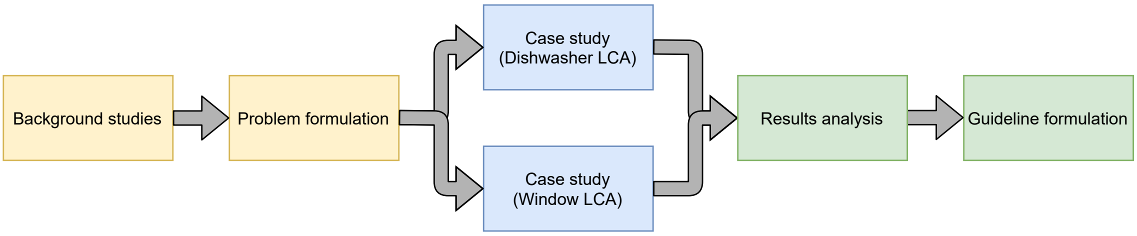


Figure 3.1: Illustration of the methodological steps, where the yellow boxes represent the studies leading up to and preparing for the case studies, the blue boxes represent the case studies and the green boxes represent the analysis following the completion of the case studies.

3.1 Background analysis

In this section, we first describe how the literature review was conducted. Then we describe how we used data and research from within the CCBuild platform, but also external sources, to analyse the context in which the digital tool is used. The purpose of this was to understand more about the potentials for reuse, but also to find relevant products to assess in our case studies, as well as to find a basis for how to categorize different products.

3.1.1 Literature review

The literature review handled definitions of linear and circular material flows, life cycle assessment as a methodology, how LCA is used within the construction industry and how reuse process can be incorporated in LCAs. The review consisted of literature from the databases such as Google Scholar and Scopus as well as other relevant reports and books. Search words which were used, individually and in combinations, were life cycle assessment, LCA, construction, reuse, linear material flows, circular material flows and circular economy, climate target, climate impact, sustainability targets in construction and building materials. The found literature is a combination of scientific articles, textbooks, statistics and product information published by stakeholders on the market. In total 109 documents have been analysed of which 52 have been used as references in this thesis.

3.1.2 Product level

In order to draw conclusions on what products are interesting to include in the inventory, and furthermore in the reuse assessment, inventory data from a specific building included on the CCBuild platform was studied (as described in section 1.2). The numerical data on product volumes was quite uncertain, and was deemed as not necessarily representative for the inventory of the building. All product types included in the inventory, regardless of frequency of occurrence, were thus deemed equally interesting.

We supplemented our insights from studying the inventory with information from published literature on the reuse processes, interviews with actors and discussions with our supervisors at IVL. A set of possible processes that can be included in the reuse phase to different extents were found, which will be discussed in section 3.2.2.

The CCBuild product tree was not used, but rather products were grouped according to use phase characteristics as shown in figure 3.2. We expected there to be a difference in use phase impacts between a new and a reused product, for products consuming some kind of resource. Many product groups utilise the same type of resource (energy, water, heating etc.) which are provided in a manner comparable between systems while being directly susceptible to differences in efficiency. Establishing guidelines with a focus on this type of characteristic thus seemed relevant, looking to the scope of the study.

As can be seen in figure 3.2, grouping of products was done on several levels. The first tier of grouping (the two orange regions in figure 3.2) was a simple division of products consuming resources and products not consuming resources. Consuming resources was considered only when being necessary to provide the service of the product. As such, products only consuming e.g. some kind of resource or material for cleaning (like detergent) are not considered to be resource consuming in this context.

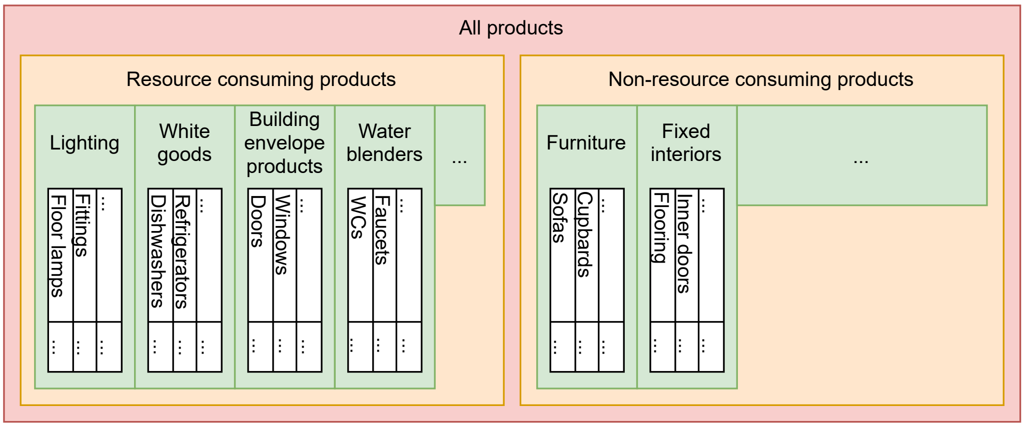


Figure 3.2: Tiered product groups based on use phase characteristics.

- The first of these two groups include e.g. appliances consuming electricity, WC's consuming water and products in the building envelope giving rise to a larger use of heating. The second group includes e.g. wash basins, cupboards and flooring, who all provide their services without having any direct effect on resource consumption.
- In the next grouping tier (the green regions in figure 3.2), the products consuming resources are divided up together with other products consuming similar resources in a similar manner.
- The last grouping tier (marked white in figure 3.2) groups products of the same product type. Products of the same type are expected to deliver the same service, but might do so with different efficiency, quality and volume.

3.1.3 Company and market level

To study the reuse processes on the company and market level, we studied published literature as well as conducted interviews with people across different functions of the industry. The purpose of this was to provide a foundation for our discussion on how to incorporate reuse into the life cycle flow modelling.

Gerhardsson et. al. [8] describes in a paper how the real estate- and construction companies work with, and perceive, reuse. They also discuss what the market for services connected to reuse look like, what functions exist, and what additional functions are needed. The paper is based on data from nine interviews with actors in different companies and one survey with 72 respondents across different functions in the construction- and real estate industries. After having studied the data supporting the paper, and referenced it with other literature, we did not see any need to conduct further investigations into the general level of circularity in the industry. This since all of our initial questions regarding this subject were answered in the survey or in other literature.

We also conducted four semi-structured interviews with actors from different parts of the industry, to supplement the information. The interviewees consisted of one sustainability coordinator at a real estate company, one manager for a retailer for reused building products, one municipality sustainability coordinator in charge of an intermittent storage facility currently being built, and one sales coordinator at a company refurbishing and selling reused office furniture. The first three are involved in different ways on the CCBuild platform, and the last one is not.

The insights from these studies was used together with the previous background studies to feed into the work on deciding how to integrate the reuse processes in the life cycle modelling.

3.2 Case studies

Based on our background studies, we decided to conduct case studies on an arbitrary window and an arbitrary dishwasher, respectively. These were chosen to give separate perspectives to the different subordinated research questions; the window (while being energy passive in itself) gives rise to energy consumption through the heating system, the dishwasher since it uses electrical energy and water. Additionally, the dishwasher has a limited technical life length. These two products also allowed to study different flows in the reuse phase.

The inductive aspect of the study was to learn, using the experiences from the case studies, how these assessments can be done on products with certain types of characteristics in the future. This in turn would let us answer our overarching research question, by formulating the guidelines. We also applied an iterative approach, moving back and forth between the stages of an LCA (described in the theory section 2.2) making updates as new findings were made affecting different parts of the study. Particularly, we studied what and how assumptions on different unknown parameter values can be made, and how to model the product life cycle flows to be relevant for different products of a similar kind.

The rest of this section is dedicated to explaining the reasoning behind the different steps of the LCA methodology used in the case studies.

3.2.1 Goal and scope

Goal definition

Since the two case studies were performed as smaller studies within the larger study, they had individual goals of their own. They are formulated thus:

The goal of these case studies is to provide results supporting decisions on whether to discard or keep old appliances in use within a building, during a renovation project. This should be done by comparing the expected effects on climate change from reusing the older unit, with the expected effects of exchanging it for a brand new unit. The assessment should be done for different values on parameters controlled by relevant characteristics in the product. In doing so, the study should account for different aspects of the older product affecting it's suitability for reuse from an environmental perspective. The LCA should be cradle-to-grave, to account for the entire comparable life time (with some standardized use-phase timespan) of the product.

Scope definition

We have chosen attributional modelling for the assessments in this study. This is motivated as follows:

- The calculation model used on the CCBuild platform uses attributional data and modelling. To enable using the results from the assessments in this report together with the results in the existing digital tool, attributional values are needed.
- The standard EN 15978 prescribes using attributional values for modules A, B and C. By doing so, we enable comparing the results from the assessments described in this study with other construction industry LCA's.
- The use phase emissions which we attempt to estimate in these assessments all lie in the future. To make an assessment, actual energy use as well as the carbon intensity of the energy use must be estimated. Since it is not possible to know for certain under what circumstances the product will be used, it is deemed appropriate to assume average values for parameters, which fits well with the attributional methodology.

Since the purpose of this study as a whole is to investigate the life cycle emissions with a focus on use and reuse processes specifically, emissions from modules A (raw material extraction and manufacturing) and C (end-of-life) were not studied in detail. Thus, a modelling choice we made specifically for the case studies were to use inventory data for these modules from other sources, rather than calculating them ourselves.

Utilizing the fact that we are making a comparative assessment, we decided to omit any flows deemed (sufficiently) equal between the options from the calculations. We also chose to omit any flow unaffected by the choice of options. Our view is that this makes the calculations much simpler, while still capturing the relevant flows that set the studied options apart.

The flows connected to reusing a product are not explicitly described by a separate module compatible with the other modules in EN 15978, as described in section 2.3.1. To facilitate the understanding and comparability of the flows connected to reuse activities, we have decided to model them in a new reuse module, which will be described further in section 3.2.2 on inventory analysis.

The number of compared options differ between the two case studies. In the window case study, three scenarios are considered, where the first (linear) scenario is compared against the second and third (circular) scenarios, respectively:

- Scenario 1: The existing window is discarded and exchanged for a new one
- Scenario 2: The existing window is reused
- Scenario 3: The existing window is reconditioned and then reused (a new glass cassette is installed)

In the dishwasher case study, two options are compared:

- Linear scenario: The existing dishwasher is discarded and exchanged for a new one
- Circular scenario: The existing dishwasher is reused

We based our choice of which parameters would be required as input from the user on the background studies. However, due to the iterative nature of the study, we continuously updated our interpretation of the relevance of the parameters after observing their respective influence on the results. This can be considered a major part in the development of the guidelines.

Flowchart

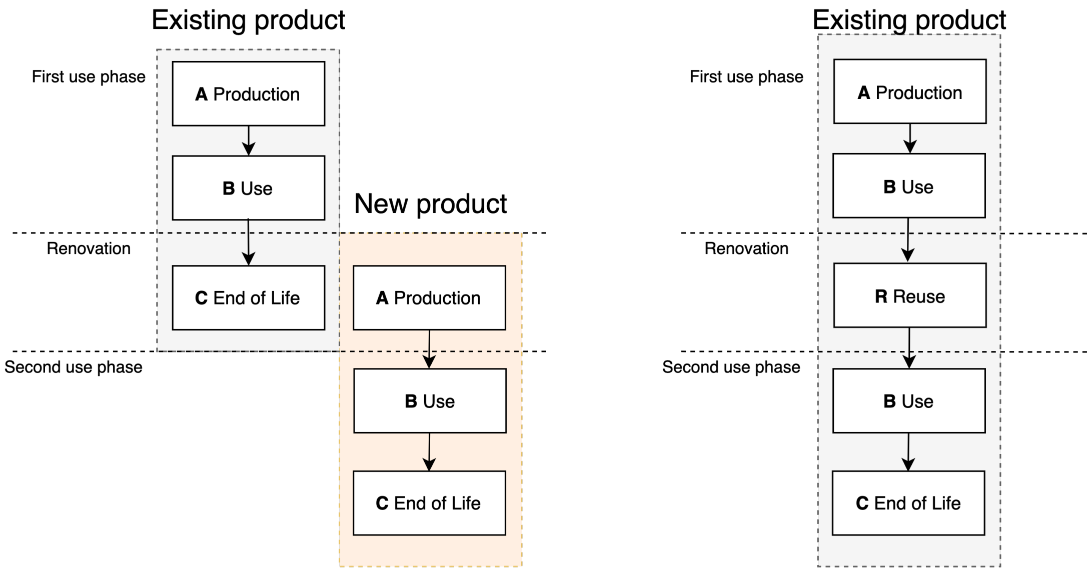


Figure 3.3: A simple, conceptual flowchart describing how we chose to model the life cycle flow of the linear and circular product flows. The linear option is to the left, the circular case to the right. ”Reuse” replaces modules C and A in the Renovation of the circular flow.

We chose to draw the flowcharts linearly, even when including circular flows like reuse, in order to facilitate understanding what processes are being compared. This entails that the circularity is illustrated as consecutive uses, as described in section 2.2. To facilitate comparisons with LCA’s conducted in accordance with EN 15978, it’s modules and processes where used to describe the flows. However, in order to account for the reuse processes the module R, *Reuse*, was added. In figure 3.3 below, you can see a simple conceptual flowchart describing the sequence of module flows for the linear and circular options respectively. A further explanation of which processes are included in this module, and how we designed it, is presented in section 3.2.2. All flows connected to the ”first use phase” are neglected, since these refer to the same product and as such can not be compared. The ”Renovation” and ”Second use phase” are rather what is compared. The final flowcharts for both the dishwasher- and the window case study are presented in appendix A and B respectively.

Functional unit

To enable comparisons between a new and an older product, we set the functional unit so as to represent the same amount of service provision between the two products. This means that the size (or capacity) of the compared products, as well as the time frame of study is set equal. For the dishwasher, which has a short and relatively predictable technical life length, this timespan was related to the expected remaining service time of the older product. This also has implications on how emissions from modules A and C are allocated towards the studied product, which is explained further in the inventory analysis section 3.2.2. For the window, which can be used for a very long time, the time span was instead fixed to a certain comparable number of years.

Based on the above, the functional unit for the dishwasher case study was chosen as: ”Dishwasher service equal to that of the older appliance, for it’s expected remaining lifetime”.

Similarly, the functional unit for the window case study was chosen as: ”Window service from a window with a specific geometric size and U-value, during 50 years”.

Impact assessment method

In the assessments we have studied one impact, being global warming (GWP100) expressed in kg CO_2-eq. This impact category is included in the assessments provided by the CCBuild digital tool today. Furthermore, a Sustainability Coordinator working in one of the real estate companies connected to CCBuild stated in an interview that climate impact is considered the most important measurement for most real estate companies. This since they usually have a company goal regarding their climate impact. She expressed that they would have a hard time coping with more indicators. In order to provide a single indicator result, we decided to only look at GWP100.

System boundaries

Since the CCBuild platform is a collaboration between Swedish construction companies, we have considered all of the use- and reuse-activities to take place within Sweden. However, we have also used data from other countries deemed comparable if necessary. Especially ones with a close connection to the Swedish market, like the countries within the EU. Values from outside Sweden have also been used for other parts of the life cycle (modules A and C) where considered appropriate, e.g. due to production taking place in other countries.

For factors varying a lot within Sweden, we have tried to make relevant delimitations, looking at either a national average or a set of values considered representative for different relevant conditions. For example, the energy required to provide water for a dishwasher varies throughout Sweden in a way that does not impact the results of the assessments noticeably. However, the carbon intensity of the district heating systems across the country varies immensely [38], making separate assessments relevant for a sample of different heating systems.

We have used cut-off for some processes deemed insignificant as a part of the emissions from the studied products' life cycles. This includes e.g. the energy use for machinery in the reconditioning processes, and resource consumption in the use phase amounting to less than 1% of the total comparable module impact.

Assumptions

We have had to make several assumptions to perform the calculations in these studies. This since we want for the system to require only small amounts of input data, and since many parameter values depend on activities happening in the future. We have in the case studies tried to make assumptions or estimations based on relevant sources from scientific literature. Where no such sources have been found, we have tried to make an assumption based on our own experiences and reasoning. Data gathering is discussed more explicitly in the inventory section 3.2.2. We also decided to perform sensitivity analyses for many of the parameters, to test and discuss what impact our assumptions have had on the results of the assessment.

Reporting and critical review

This Master's thesis will be opposed by a peer also enrolled in the second year of the Industrial Ecology M.Sc. program at Chalmers University of Technology, as well as opposed and graded pass/fail by an examiner who is currently working as a researcher at the Department of Technology Management and Economics, Division of Environmental Systems Analysis at Chalmers University of Technology. The thesis will be presented publicly in a seminar allowing for open questioning of the result.

Actors

The actors affected by the result of the case studies were considered to be people involved in a renovation project. This includes people involved in the CCBuild platform, like people working in real estate, construction and local government.

3.2.2 Inventory analysis

All calculations regarding the climate impact from each studied module for the window and dishwasher case studies are presented in appendix C and D respectively.

Module A

The flows connected to module A are considered as a part of the ”Renovation” flow in the linear option shown in figure 3.3. Below, in figure 3.4, the module is shown with it’s processes included. Processes A1-A4 are considered in the assessment, while A5 is omitted due to cancellation with process R5 in module R, described later in this section. The data on emissions from processes A1-A4 was thus gathered from either CCBuild or other external sources such as Boverket’s database [26] and scientific literature [39].

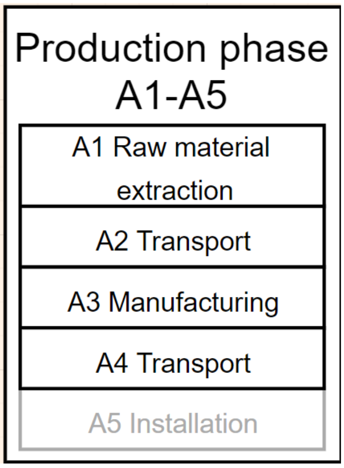


Figure 3.4: Module A, included in the life cycle renovation section of the linear option. Processes A1-A4 are included, while A5 is omitted from the calculations due to cancellation with the R5 process of the reuse (R) module.

When comparing a new and a reused product of a limited technical service life, the entire module A emissions can not be included in the assessment. Since the new product will continue to benefit from the emissions from module A after the reused dishwasher is expected to stop working. it is only fair to consider the module A emissions relative to the share of the remaining technical service life left for the older product. This is illustrated with an example in figure 3.5. For a product of a longer technical service life, like the window, the compared products can be expected to function for the same amount of time, and the same division between their remaining service lives would thus result in 1.

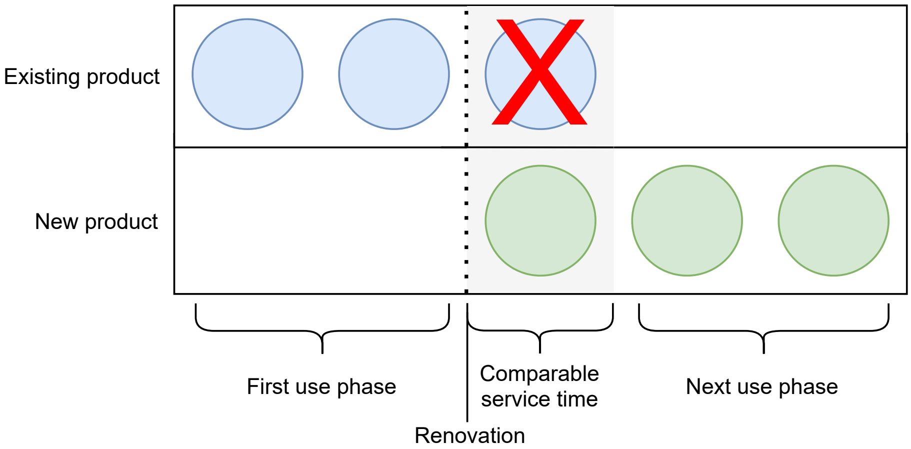


Figure 3.5: Comparison of technical service time for different products. Assume that an arbitrary product of a certain type has an expected technical lifetime of three time units, here represented by circles. In this example, we imagine that the building is renovated after the first product has been operational for two time units, and the product is exchanged for a new product. Reusing the older product can only be compared to a third of the impacts from the new product.

Module B

In this module, some processes were omitted in the assessments, as shown in figure 3.6. B1 ”Use” and B2 ”Maintenance” were considered to be inherently dependent on the behaviour of the user, and thus not depend on the choice of option. B3 ”Repair” is also omitted, since the uncertainty about how often a product needs repair is large [40][41]. We thus assume that the compared products will require the same amount of repair during the observed time.

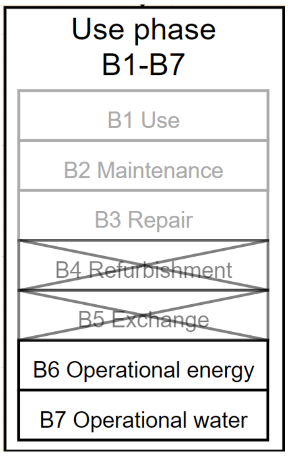


Figure 3.6: Module B, included in the second use phase of both the linear and circular options. Processes B6-B7 are included in the assessment. B4-B5 are considered outside of the scope, and B1-B3 are considered to cancel out between the two options.

Processes B4 ”Refurbishment” and B5 ”Exchange” are considered outside of the scope of this study. This is an effect of the process-based, bottom up modelling, which is discussed in section 2.4.2. Refurbishment would entail choosing to actively reuse a product, meaning that the life cycle flow would proceed into the R module for that particular product. The life cycle of either of the products is considered to end if the product is exchanged for another, which means that exchange will never occur as a part of the life cycle flow of the particular product.

Following, we describe how processes B6 and B7 were used in the different case studies.

Window, module B

In the window case study, B6 includes the heat consumption required to make up for the heat lost through the window. As such, a comparison could be made for the emissions from the required heat production for the different options during the studied time period. We assumed that all heat was produced in the local district heating system. This was calculated using the following parameters:

- U-value of the studied window, which affects how much heat is lost per unit area
- Area of the studied window
- Outside and inside temperature, the difference between which affects how much heat is lost per unit area
- Carbon intensity of the district heating grid, to determine the GHG-emissions per unit of energy
- Observed time of the study, to calculate the cumulative emissions

In figures 3.7 and 3.8, the comparisons for the different scenarios, and which U-values were assumed for the respective inputs, can be seen. The different U-values for the respective scenarios depend on the glass cassette construction of the window. The compared options were considered to have the same area for all comparisons.

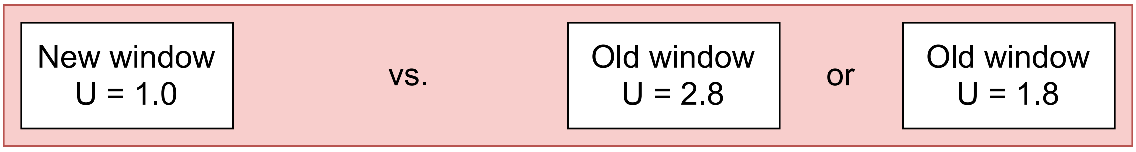


Figure 3.7: Comparison of scenario 1 and 2. The assumed U-value of the new window is based on recommendations from a Senior Technical Advisor at SP Fönster. The two assumed U-values for the old window in scenario 2 are based on standard U-values for traditional (without low emission glass) 2-glass windows and 2+1 and windows [42] [43].

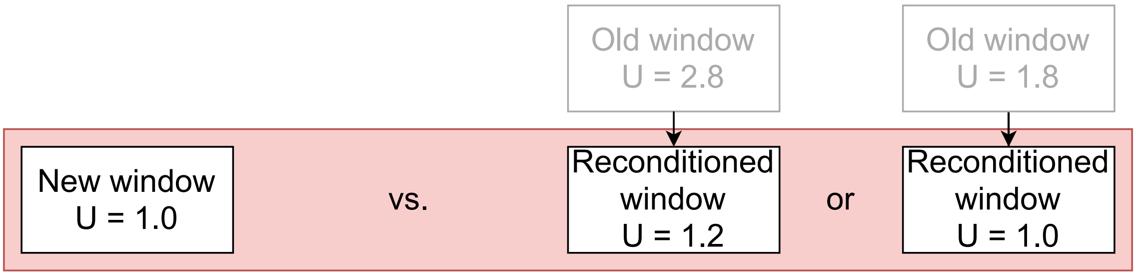


Figure 3.8: Comparison of scenario 1 and 3. The assumed U-value of the new window is based on recommendations from a Senior Technical Advisor at SP Fönster. The two assumed U-value of the reused window in scenario 3 are based on the stated U-value reached when installing a new isolation glass cassette in a old 2-glass window and a 2+1-glass window with the corresponding U-values assumed in scenario 2 [42] [43]

To account for differences in district heating, we performed the assessments for three different district heating networks. This was done in order to analyse how the variations in carbon intensity between different networks would effect the appropriateness to reuse a window in different locations. Also, the local hourly outside temperature (based on measurements from 2019) was included in the assessment for each municipality. The inside temperature was set to a constant of 20°C since it is within the frame of what the Swedish work environment association considers a good indoor temperature [44]. The studied municipalities, and the carbon intensity of their respective district heating systems, were:

- Stockholm, Stockholm Exergi (0.065 kg CO_2/kWh)
- Linköping, Tekniska Verken (0.103 kg CO_2/kWh)
- Kungsbacka, Statskraft Värme (0.012 kg CO_2/kWh)

Dishwasher, module B

In the dishwasher case study, the flow connected to B6 ”Operational energy” included the annual electricity consumption for running the dishwasher and having it on standby. The energy label for a dishwasher is used to estimate an annual electricity consumption of a specific appliance, and in turn compare the use phase emissions between the older dishwasher and a new one. The new dishwasher is considered to have the highest available energy label in the Ecodesign Regulation (EC) No 1016/2010 [45]. To account for future increases in energy efficiency, the assumed energy efficiency of the new dishwasher can be adjusted in the background data of the system to represent the best appliance on the market. How the annual electricity consumption was calculated is explained in appendix E. The parameters used were:

- Annual energy consumption of the older dishwasher, which was assumed according to dishwashers energy label
- Capacity of the dishwasher, which affected how the annual energy use is calculated for the given energy label

- Year of installing the older dishwasher, to estimate the remaining expected technical life length
- Carbon intensity of the electrical grid, to determine the the GHG-emissions per unit of energy

The size and comparable use phase time are considered equal between the new and the older dishwasher. We performed the assessments for ”Large” and ”Small” dishwashers, which can take 13 and 9 place settings respectively, as these sizes are deemed the most common [45]. The total technical service time was set to 12.5 years, as found by Tecchio et. al. [40], and the remaining technical service time was used as the observation period for the study. The carbon intensity of the Swedish electrical grid was estimated as a single average value, gathered from a report by Moro and Lonza [46]. This since the carbon intensity on the electrical grid fluctuates constantly, and is connected across the nation and interlinked with the electricity market of northern Europe. This made us consider an average value to be the best estimation of the carbon intensity. We do not consider that the carbon intensity of the electricity might become lower with time, in order not to risk underestimating climate impacts.

We assumed that all dishwashers of a certain energy label had an as low energy efficiency as was allowed for that label, which is supported by findings by Boyano et. al. [45]. The choice of comparison options are shown in figure 3.9.

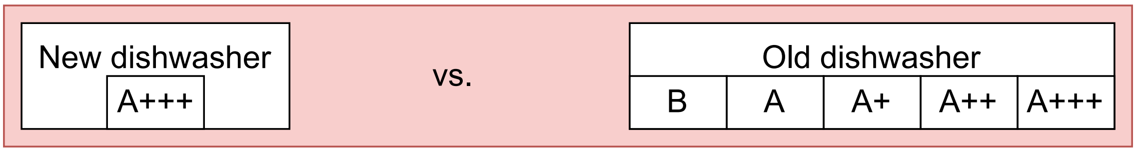


Figure 3.9: Comparison between a new and an old dishwasher. The energy labels are set by the EU, with B being the lowest and A+++ being the highest. This labelling scheme was in force until the 1st of March 2021, while this report was written. However, the same principle for calculating energy consumption (which is demonstrated in appendix E) can be used with the new system.

Process B7 ”Operational water” was included as a flow in the use phase of the dishwasher case study. The water use in a dishwasher requires energy to pump and purify the water on the municipal grid. A previous study had found the median energy use for pumping and purifying a cubic meter of water across the water treatment facilities in Sweden [47]. Since water use efficiency is not included in the energy labelling, we assumed that a dishwasher with better energy efficiency should also have a somewhat better water use efficiency, and assigned an average yearly water consumption to each respective energy label accordingly. The energy use from this water consumption could then be added to the operational energy use, and together a yearly average emission could be calculated for the use phase.

Module R

The processes connected to reuse are not described in a specific module in EN 15978, as explained in section 2.4.1. Reuse of products are often not considered a life cycle-loop, but rather a part of the use phase [28] [24] [29]. This module is a suggestion that we have designed as a part of this study, to emphasize the reuse activities in the life cycle. It is only part of the circular option shown to the right in figure 3.3.

We have chosen to include four processes in the calculations, as shown in figures 3.10 and 3.11. These account for the need to store and repair products, and transport to and from these activities. These activities were chosen with inspiration from previous works at IVL [24].

All of these processes will not apply to the R module of all products. A dishwasher would be repaired immediately upon breaking down; repairs are thus part of it's use phase. When studying several windows, only some of them might be in need of repair. The R module can thus look different, either between product types or between individual products. R5 ”Installation” is included in the module, but omitted from the calculations due to cancellation with the A5 process of the A module in the linear option.

Both processes R1 and R3, representing transportation, entail emissions from fuel combustion. This depends on a number of variables, like:

- Transportation distance
- Mode of transportation (both vessel- and fuel type)
- Fill rate of the vessel
- Weight of the product

The first three parameters on the above list were set based on the assumptions made by IVL when calculating the climate impact of transport in connection to reuse in the current version of the CCBuild tool. The weight of the product was specified for each product type, depending on size.

In the storage unit, the different energy uses need to be allocated among the products kept inside. This was done by assigning each product with the share of the emissions from storage relative to the share of the occupied floor space used by the product. The assumed values were based on interviews with stakeholders in the storage sector.

Reconditioning a product, in this case a window, can be executed in many different ways [43]. In order to not underestimate the emissions from the reconditioning process, we have assumed that the entire glass cassette is exchanged. Thus, we have used the inventory data for producing a glass cassette [48], since no separate data for spare parts was found. This most likely instead an overestimation, which should be kept in mind. We also studied waste treatment of the old glass cassette, but the impacts from this was negligible and thus excluded. We also studied the impacts from cleaning and painting the old window. These were deemed negligible as well.

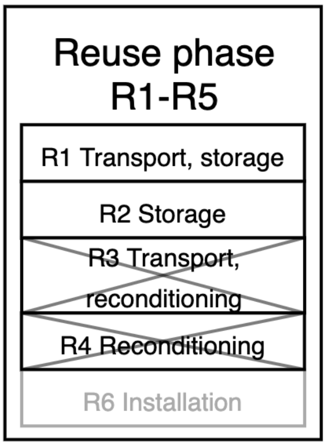


Figure 3.10: Module R, included in reuse scenarios where no reconditioning is performed. Processes R1-R2 is included in the assessment. R3-R4 are considered outside of the scope, and R5 is omitted from the calculations due to cancellation with process A5 in module A.

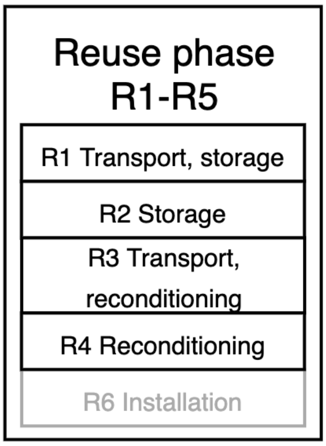


Figure 3.11: Module R, included in reuse scenarios where reconditioning is performed. Processes R1-R4 are included in the assessment. R5 is omitted from the calculations due to cancellation with the A5 process of the module A.

Module C

Module C, like module A, is included in the assessments as a part of the linear "Renovation" flow in figure 3.3. The C module occuring after the second use phase is considered to cancel out between the two options. All processes of module C is included in the assessments.

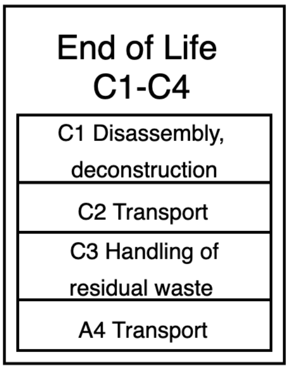


Figure 3.12: Module C, included in the life cycle renovation section of the linear option. All processes are included in the calculations. This module is omitted from the Second use phase, due to cancellation.

Also like module A, the flows connected to module C has been handled with a lower level of detail than modules B and R, and as such values for this module has been gathered from either CCBuild or other, external sources.

A third thing similar between modules A and C, is the way they are affected by the chosen observation time in the dishwasher case study. In the same manner explained for module A, the emissions from module C is included in the assessment relative to the comparable remaining technical service life of the older product. This means that the share of module C emissions considered in the assessment will be the same as the share of the expected remaining service life. See figure 3.5 for a graphical explanation.

3.2.3 Impact assessment

In this stage of the case studies we summarized the impacts according to the chosen impact category. Since we had only chosen one impact category, global warming (100 years), and had gathered all the inventory data expressed in kg CO_2-eq, there was no need for explicit classification, nor to convert the emissions through characterization.

Instead, we used the impact assessment stage to test the results for different inputs to the system, using the assumptions specified throughout the assessment. For the dishwasher case study, this meant calculating the net difference in GHG emissions between reusing and buying a new dishwasher for different sizes, energy label and years of use. For the window case study, it meant calculating the net change in GHG emissions from reusing or reconditioning a window with different U-values over buying a new one in different municipalities, with regards to historic weather and district heating system. We could then draw conclusions on the results.

3.2.4 Sensitivity analysis

The sensitivity analyses were designed to test how the assumptions we had made held up under different circumstances. Since many of the parameters depend on future behaviour and technical development etc., and many parameters were given as an assumed fixed value in order to narrow the amount of information needed by the user of the CCBuild digital tool, it was deemed appropriate to test how the results would be affected if the assumptions would turn out to be wrong.

We studied variations in five parameters in the dishwasher calculation model and six parameters in the window calculation model. The five studied parameter variations in the dishwasher case study were:

- **Frequency of use**: Using the dishwasher 470 times in a year (twice every working day for 47 weeks) instead of the assumed 280 times.
- **Expected technical service life**: Assuming a two years shorter or longer expected technical service life compared to the original assessment (10.5 years and 14.5 years respectively).
- **Energy efficiency at water treatment facility**: Assuming the highest or lowest energy efficiency for municipal water treatment observed by the SVU

[47], instead of the median.

- **Different modes of transportation and distances to reuse storage**: this was the only sensitivity analysis looking at two parameter changes simultaneously. We calculated the result when transporting the product double and half the distance respectively, for three different modes of transportation with different levels of assumed emissions per tkm (tonnes · km), based on data retrieved from [49]:
  - Van: 0.799 kg CO_2-eq/ton·km
  - Light duty vehicle: 0.557 kg CO_2-eq/ton·km (assumed in the original assessment)
  - Rigid truck: 0.223 kg CO_2-eq/ton·km

  These combinations rendered six different sensitivity analysis results. The same sensitivity analysis was conducted for the window case study.
- **Storage time for reuse**: Storing the product for 3 months or 24 months instead of the assumed 6 months since storage time may vary in different projects depending of their time span. The same sensitivity analysis was conducted for the window case study.

The six studied parameter variations in the window case study were:

- **U-value for different window types**: Increasing the assumed U-value by 0.2 $W/m^2{\cdot}K$ for both of the assessed window types, from 2.8 $W/m^2{\cdot}K$ to 3.0 $W/m^2{\cdot}K$ and from 1.8 $W/m^2{\cdot}K$ to 2.0 $W/m^2{\cdot}K$ respectively. This is based on the fact that U-values usually range from 2.8 to 3.0 and 1.8 to 2.0 respectively for the different window types [50].
- **Higher/lower indoor temperature**: Assuming a 2°C higher or lower indoor temperature compared to the original assessment (22°C and 18°C respectively).
- **Averaging outdoor temperature**: Instead of using hourly, local data for the outdoor temperature we here studied the effects on the results from three other ways of gathering weather data:
  - Monthly, local weather data
  - Yearly, local weather data
  - Monthly, national weather data
- **Different modes of transportation and distances to reuse storage**: Conducted in the same manner as described above for the dishwasher case study.
- **Shorter/longer storage time for reuse**: Conducted in the same manner as described above for the dishwasher case study. Additionally, the effect of storing a product in a municipality with cleaner/dirtier district heating was studied, since this data was available from the case study.
- **Materials for reconditioning expressed as a share of the total product weight**: Using the share of the total emissions for producing a window relative to the share of the total weight of the part being exchanged, instead of finding specific emissions data for the replacement part. This was conducted for exchanging the glass cassette.

Having completed the sensitivity analyses, the results were later used to discuss how to handle the assumptions going forward.

3.2.5 Interpreting the case study results

The results from the original assessments in the case studies were studied together with the effects on the results observed in the sensitivity analyses. Together with the experiences from performing the case studies, we could then put together a set of guidelines for producing further calculation models for other product categories with related characteristics. These will be presented in the results section.

4

Results

In this chapter results from the case studies will be presented, followed by their respective sensitivity analyses. Finally, the concluded guideline for how to model and calculate the difference in climate impact when reusing a product instead of installing a new one will be presented. This includes recommendations, formulated to make these results reproducible for more products types. The guidelines in themselves are the answer to the overarching research question; their explanations are the answer the subordinated research questions. The guideline will contain suggestions for how calculations for each process may be conducted as well as which data that may be based on generic assumptions and which that need to be specifically inventoried for each product.

4.1 Results from the case studies

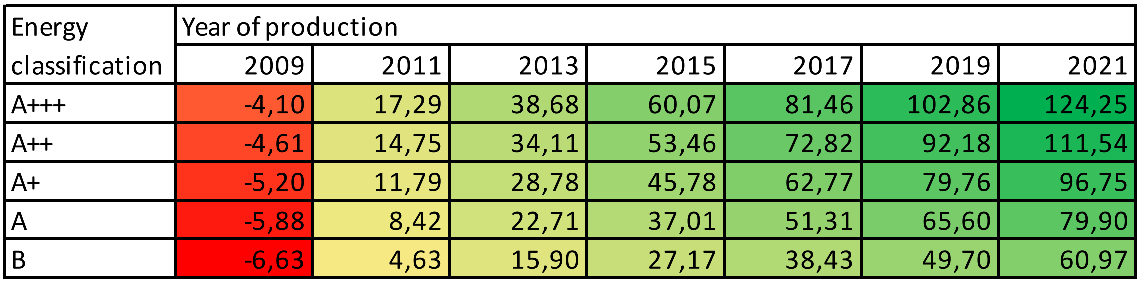
Calculations for both case studies are presented in appendices C and D respectively.

4.1.1 Dishwasher case study

The result presented by the assessment, for the decision maker, is the difference in life cycle emissions between the linear- and circular option. It is either given with a positive number (indicating net avoided emissions) or a negative number (indicating net emissions) from reusing the older dishwasher for the specified observation time.

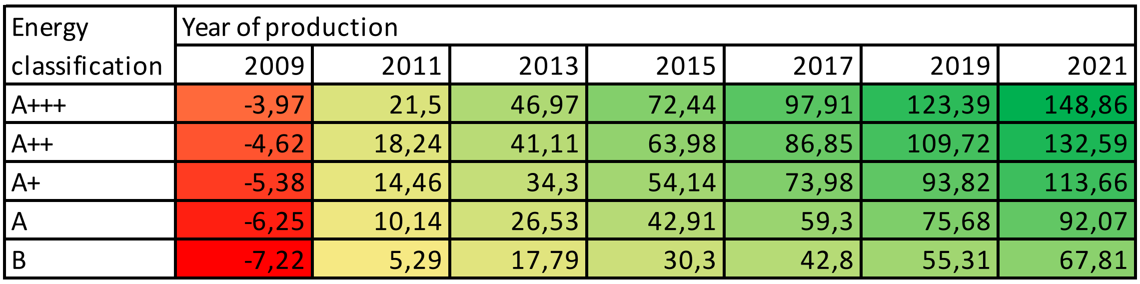
The results are shown for two different sizes, a "Small" and a "Large" dishwasher (as defined in section 3.2.2) in two separate tables given in figures 4.1 and 4.2 below. The results are in each table given for the different possible inputs in energy label (signifying annual energy consumption) and a sample of different years of production (affecting the expected remaining service time). Remember that these inputs apply to the older dishwasher, and that the new dishwasher (the linear option) is assumed to have the highest energy label for all comparisons.

As is evident from this compilation of assessment results, the newer and more energy efficient a dishwasher is, the larger the avoided impact from reusing it. Comparing the two tables, it can also be seen that a reusing a larger dishwasher entails larger savings compared to a smaller one of the same age and efficiency. With appliances produced 2009 and earlier, reusing implies a net emission. This is a result of the short expected remaining lifespan.



Energy classification	Year of production						
	2009	2011	2013	2015	2017	2019	2021
A+++	-4,10	17,29	38,68	60,07	81,46	102,86	124,25
A++	-4,61	14,75	34,11	53,46	72,82	92,18	111,54
A+	-5,20	11,79	28,78	45,78	62,77	79,76	96,75
A	-5,88	8,42	22,71	37,01	51,31	65,60	79,90
B	-6,63	4,63	15,90	27,17	38,43	49,70	60,97

Figure 4.1: Avoided emissions from choosing to reuse a small dishwasher, for different energy labels and a sample of different production years, given in kg CO_2-eq. The new, compared dishwasher is assumed to have the energy label A+++.



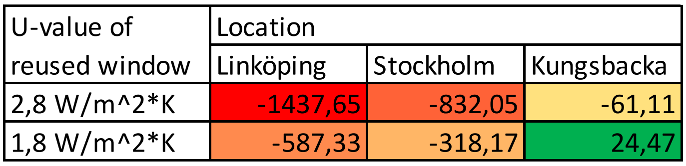
Energy classification	Year of production						
	2009	2011	2013	2015	2017	2019	2021
A+++	-3,97	21,5	46,97	72,44	97,91	123,39	148,86
A++	-4,62	18,24	41,11	63,98	86,85	109,72	132,59
A+	-5,38	14,46	34,3	54,14	73,98	93,82	113,66
A	-6,25	10,14	26,53	42,91	59,3	75,68	92,07
B	-7,22	5,29	17,79	30,3	42,8	55,31	67,81

Figure 4.2: Avoided emissions from choosing to reuse a large dishwasher, for different energy labels and a sample of different production years, given in kg CO_2-eq. The new, compared dishwasher is assumed to have energy label A+++.

4.1.2 Window case study

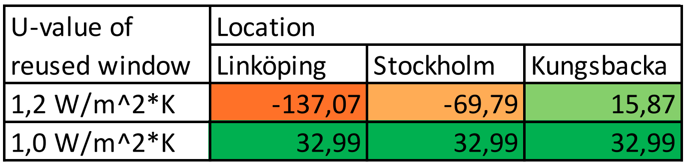
This assessment was made to estimate the effect on net avoided emissions, from reusing windows. These so called scenarios are described in section 3.2.1. Two results are thus presented for the user: first, the difference in emissions between scenarios 1 and 2, where installing a new window is compared with reusing the old window as is. Second, the difference in emissions between scenario 1 and 3, where installing a new window is compared with reusing the old window which has been reconditioned in order to lower its U-value. The results are given with a positive or negative number showing the net avoided (if positive) or net emitted (if negative) emissions from reusing the older window for the specified observation time. Avoided emissions, first for a reused and second for a reconditioned window, are shown in figure 4.3 and 4.4 for two different U-values and three different locations (effecting the carbon intensity from district heating) respectively. Remember that the new window (scenario 1) is assumed to have an U-value of 1.0 $W/m^2{\cdot}K$ for all comparisons.

As is shown in the tables, the results vary widely depending on the characteristics of the product. The largest differences, however, depend on which municipality the building is located in (or, more precisely, which district heating network it is connected to). Reusing a window with a high U-value is never beneficial; reusing a window with the lowest assumed U-value is always beneficial, since it does not entail higher energy demands. Reusing a window with U-value 1.8 W/m^2·K, or reconditioning one to get U-value 1.2 W/m^2·K, is beneficial if the building is located in Kungsbacka (because of the relatively low carbon intensity this district heating network).



U-value of reused window	Location		
	Linköping	Stockholm	Kungsbacka
2,8 W/m^2*K	-1437,65	-832,05	-61,11
1,8 W/m^2*K	-587,33	-318,17	24,47

Figure 4.3: Net avoided emissions from choosing to reuse a window, for a sample of different locations and U-values, given in kg CO_2-eq. The new, compared window is assumed to have U-value 1.0 W/m^2·K. This figure show the results from comparing scenario 1 and scenario 2, where the old window is reused as is.



U-value of reused window	Location		
	Linköping	Stockholm	Kungsbacka
1,2 W/m^2*K	-137,07	-69,79	15,87
1,0 W/m^2*K	32,99	32,99	32,99

Figure 4.4: Net avoided emissions from choosing to reuse a window, for a sample of different locations and U-values, given in kg CO_2-eq. The new, compared window is assumed to have U-value 1.0 W/m^2·K. This figure show the results from comparing scenario 1 and scenario 3, where the old window is reconditioned before reuse. The U-value presented in this table is thus the U–value that the window has received *after* having been reconditioned.

4.2 Sensitivity Analyses

Sensitivity analyses have been performed for some of the parameters used in calculating the assessment results. Why these were chosen, and how the analysis was performed, is described in section 3.2.4. In the following two sections, we will first present a table of the parameters studied in the sensitivity analyses. Following, there will be a brief statement of the findings from each sensitivity analysis. All numerical results from the sensitivity analysis are presented in appendix F and G.

We have used different words to describe the general effects of changing the parameters under certain circumstances. These are defined as follows:

- *Small*: There is a difference in the results, but it is small (the difference is <10%).
- *Noticeable*: The results are different, but the interpretation of the results is similar (the difference is >10%, <25%).
- *Significant*: The results are different, affecting how the results might be interpreted (the difference is >25%)

- *Change of character*: If the character of the results has changed, this means that the results has changed sign; i.e. a result saying that reuse implies a net emissions saving will now say that reuse implies a net emission.

4.2.1 Sensitivity Analysis - Dishwasher

For the dishwasher, variations in five parameters were tested, as described in section 3.2.4. These are shown in table 4.1. The results of the assessment under each of the studied parameter variations can be seen in appendix G. These results are described individually below.

Table 4.1: The different parameters studied in the sensitivity analysis of the dishwasher. The table shows the value assumed in the original assessment, and what values were tested in the sensitivity analysis. The different modes of transport imply different emissions per tkm, as described in 3.2.4.

	Assumption	Tested value(s)
Frequency of use	280 uses/year	470 uses/year
Expected technical service life	12.5 years	10.5 and 14.5 years
Energy efficiency at water treatment facility	1.67 kWh/m^3	0.83 and 4.05 kWh/m^3
Different modes of transportation and distances to reuse storage	200 km, with: Light duty vehicle	100 and 400 km, with: Van Light duty vehicle Rigid truck
Storage time for reuse	6 months	3 and 24 months

Frequency of use

If the dishwasher is used more frequently than assumed, the emissions saving will be lower than estimated in the assessment (unless the reused dishwasher has the same energy label as the new one). The difference is significant for dishwashers with low energy efficiency, but small for dishwashers with high energy efficiency.

Expected technical service time

Lowering the expected technical service life of a dishwasher to 10.5 years significantly lowers the estimated emissions saving from reusing older appliances. Newer appliances are not affected to the same extent (the difference is noticeable or small), and newer appliances with a low energy efficiency even receive a higher estimated emissions saving.

On the contrary, increasing the expected technical service life of a dishwasher to 14.5 years significantly increases the estimated emissions saving from reusing older appliances. Again, newer appliances are not affected to the same extent (the difference is noticeable or small), except for newer appliances with a lower energy efficiency who receive a lower estimated emissions saving.

Energy efficiency at local water treatment facility

Varying the energy efficiency at the local water treatment facility only affects the total expected emissions saving 1-3% at most, especially for dishwashers with low energy efficiency. The impact on the total results of the assessments is small.

Reuse transportation distances and modes

For driving 100 km, the total expected emissions saving is larger whichever mode of transportation is chosen. For an older dishwasher, the difference is significant, while newer dishwashers are not affected to a great extent (small difference).

For driving 400 km, the total expected emissions saving is larger if choosing to transport by a rigid truck. If a light duty vehicle or van is chosen, the total estimated emissions saving from reusing the appliance is lower. Again, older dishwashers are more significantly impacted, but if a van is used, newer appliances will have a noticeably lower emissions saving as well.

Storage time

If assuming a storage time of 3 months, there is a noticeable increase in expected emissions savings for the oldest dishwashers, and a small increase for newer ones.

If instead assuming a storage time of 24 months, there is a significant decrease in the expected emissions savings for all but the newest dishwashers, whose expected emissions saving decrease noticeably.

4.2.2 Sensitivity Analysis - Window

For the window, variations in six parameters were tested, as described in section 3.2.4. These are shown in table 4.2. The results of the assessment under each of the studied parameter variations can be seen in appendix F. The results of varying each parameter is described individually below.

U-value

If increasing the U-value by 0.2 W/m^2·K, the expected emissions saving from reusing that window is lowered slightly in relative terms. The result is affected noticeably for windows in buildings connected to a district heating system with low carbon intensity. The effect on the results for windows in buildings connected to a district heating system with high carbon intensity is small.

Table 4.2: The different parameters studied in the sensitivity analysis of the window. The table shows the value assumed in the original assessment, and what values were tested in the sensitivity analysis. The different modes of transport imply different emissions per tkm, as described in 3.2.4.

	Assumption	Tested value(s)
U-value	1.8 W/m^2·K 2.8 W/m^2·K	2.0 W/m^2·K 3.0 W/m^2·K
Indoor temperature	20°C	18 and 22 °C
Outdoor temperature	Local, hourly, recent data	Local, monthly, average data Local, yearly, average data National, monthly, average data
Different modes of transportation and distances to reuse storage	200 km, with: Light duty vehicle	100 and 400 km, with: Van Light duty vehicle Rigid truck
Storage time and space energy carbon intensity for reuse	6 months 24.0 kg CO$_2$/m^2·year	3 and 24 months 6.6 and 32.1 kg CO$_2$/m^2·year
Reconditioning materials	Spare part emission	Spare part weight percentage emission

Indoor temperature

Increasing or decreasing the assumed indoor temperature by 2°C decreases or increases the expected emissions saving somewhat, respectively. The effect on the total results is small.

Outdoor temperature

Using local, average weather data, either yearly or monthly, has a small effect on the expected emissions saving compared to using hourly, recent data. Using national, average weather data however, has a significant effect on the results. For a building connected to a district heating grid with a low carbon intensity, we even observed a change in the character of the results.

Reuse transportation distances and modes

For windows in buildings connected to a district heating grid with an average or higher carbon intensity, the effect on the total results of varying transportation modes and distances is small. For buildings connected to district heating systems with low carbon intensity, variations in transporting the windows for reuse has a more significant effect.

Storage during reuse

If the window is used in a building connected to a district heating grid with low carbon intensity, the expected emissions saving is noticeably lower if it is stored for 24 months in a storage facility connected to a district heating network with high carbon intensity. Otherwise, variations in storage time and the area unit carbon intensity of storage has a small effect on the total results.

Reconditioning emissions

For the studied part (the glass cassette), using the share of the emissions for producing a new window relative to the weight percentage of the exchanged part had a small impact on the results, compared to using the actual emissions data for producing a new part.

4.3 Guideline for the comparative flow model

Based on the findings and experiences from the two case studies, a flow model has been compiled as a guideline for conducting comparative LCA's of a new building material against a reused building material. The flowchart is presented in figure 4.5.

The flow model is divided into three life cycle stages; *First use phase*, *Renovation* and *Second use phase*. The modules included in the First use phase inherently cancel out of the assessment, since they describe the exact same product. In the Second use phase, use phase flows are compared between the two options, but module C emissions are considered to cancel out. In Renovation, all modules are considered. However, for products with a limited technical service time, only a certain share of the linear module A and C emissions relative to the expected technical service life of the reused product should be included in the assessment. This is explained further in section 3.2.2.

The flowchart in figure 4.5 is conceptual. When applying it to a product, one will have to make adjustments to that particular product, hopefully making use of the results of this thesis. Processes written out in black in figure 4.5 are considered to be relevant to include in the life cycle flow of a product. However, not all processes are compatible with all product types, or with all individual products. Process B7 ”Operational Water”, for instance, is not included in the life cycle of the window. It can therefore be entirely excluded from the analyses of products of that product type. Other processes, such as R2 ”Storage”, will (or will not) be relevant for different *individual* products, perhaps different on a case to case basis. Whether to include that process could then potentially be left to the user.

The crossed out processes in figure 4.5, B4 ”Refurbishment” and B5 ”Exchange”, should be excluded for all products since these are considered outside of the scope for this type of analysis, as motivated in section 3.2.2.

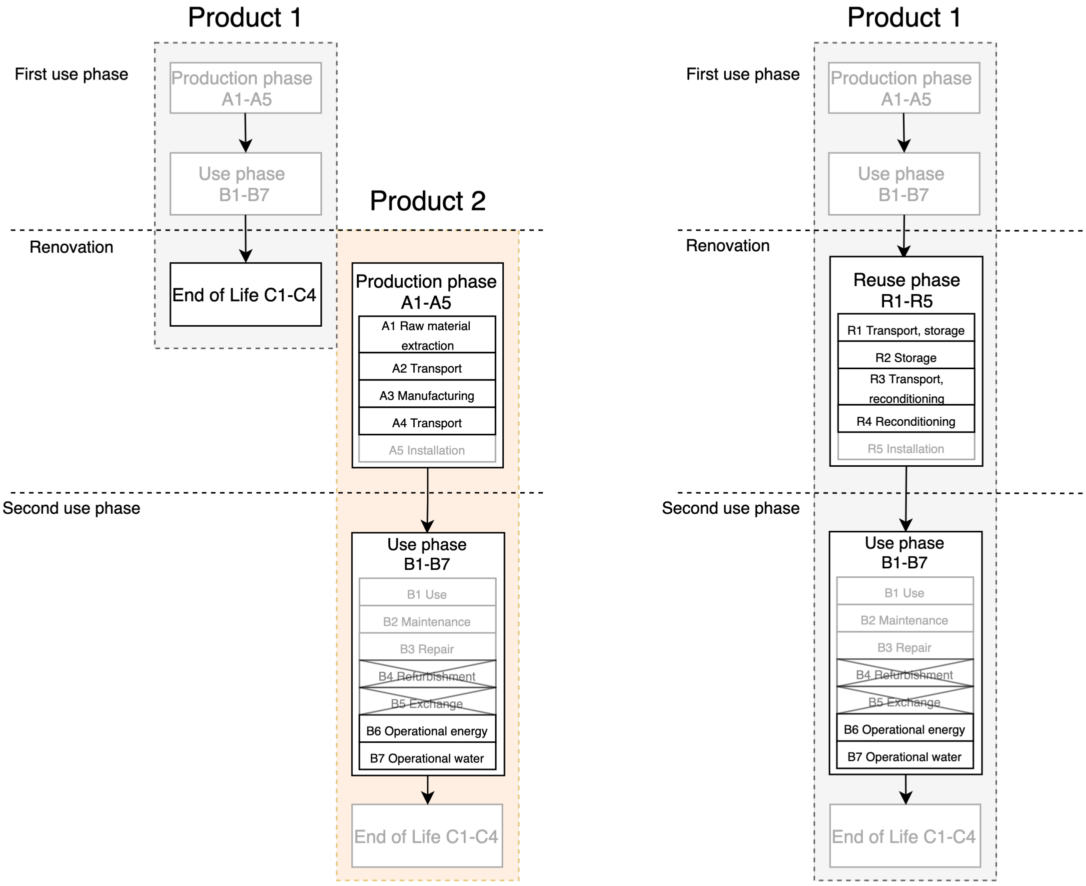


Figure 4.5: Life cycle flowchart of the two compared alternatives. Linear option to the left, circular to the right. Faded modules or processes are omitted from the comparison due to cancellation, crossed out processes are omitted since they are outside of the scope.

The processes which are faded in the flow model can be omitted from the calculations for all product types, due to the comparative nature of the study. These processes are assumed to be equal between the linear and the circular alternative and thus cancel out when calculating the difference in climate impact. In theory, there might be product types for which the impact from one of these processes may differ between an old and a new product, e.g. if a new product more efficiently utilizes a resource that is not energy or water. We have not come across any examples where this is the case, but if one would encounter such a situation, e.g. processes B1 ”Use” might be appropriate to include in the comparison.

4.4 Guideline for comparative calculations

In the following sections, guidelines for how to handle each parameter needed in order to assess the difference in life cycle GWP100-impact between a linear and a circular option for sourcing a product will be presented. The level of accuracy needed for each parameter is also described. This has implications for whether or not product specific data should be required from the user, or if generic assumptions can be used in the background system of the tool.

In this study, case studies have been performed on two products, which means that their respective characteristics have been carefully considered and represented in the results. For products with other characteristics, this guideline may also be used as inspiration for how to perform this type of assessment. Parameters might then behave differently, and the significance of certain parameters in relation to the products total life cycle impact may vary a lot. Thus, the level of accuracy needed for the necessary parameters may therefore also differ from what is suggested in this guideline.

All parameters presented in the following sections are connected to the mathematical method used in order to calculate the impact for all included processes. A conceptual model for the calculations in the guideline are shown in figure 4.6 The guideline for how to conduct the calculations with all necessary equations are presented in appendix H.

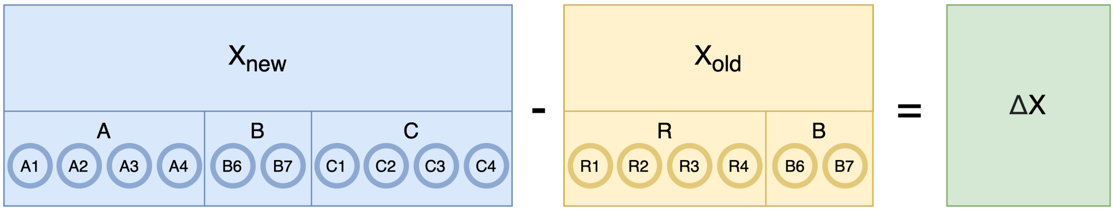


Figure 4.6: A conceptualised model visualizing how the difference in climate impact between the new and the reused product is calculated.

4.4.1 Production and End-of-Life (Modules A & C)

The values connected to modules A and C should be calculated according to models already incorporated into the CCBuild digital tool. An assumption for this study has been that this should continue.

What we have found, however, is that for product types with a limited technical lifespan, the entire module A and C emissions should not be included in the comparative assessment. Emissions from discarding the old product and producing a new one should be included in the life cycle flows of the linear option, but only relative to the remaining share of the total technical life time expected with the reused product, as demonstrated in figure 3.5.

4.4.2 Use phase (Module B)

The two processes included in the use phase are B6 ”Operational energy” and B7 ”Operational water”. In terms of operational energy a product may consume electricity in order to supply it’s service, as for a dishwasher, or a product may give rise to higher energy consumption to compensate for the heat loss through a window. Throughout this thesis it has been found that consumption of district heating and electricity are the two most relevant uses of energy in a building. It has also been found that products consuming these types of energy should be handled somewhat differently in this kind of assessments, and as such have been studied separately in the two case studies. The calculation guidelines, while applying to the same flow model, are thus differentiated to be applicable to white goods (and other electrical products), and products in the building envelope, separately. Therefore the guideline for how to calculate the climate impacts from process B6 are presented separately for the two different product categories. How to handle process B7 is then presented below.

B6 Operational Energy - Building envelope product

When using the equations in this guideline (presented in appendix H, section H.1.1) in order to calculate the difference in emissions from energy (heat) production that the studied old product would give rise to compared to a new one, certain data is needed. For the CCBuild valuation tool the following suggestions are made regarding how to handle each parameter needed in order for the calculations to present a result reliable enough for decision making. The parameters in the list are marked with a symbol, representing whether they need product- or case specific input (⊙) or if they can be included as background data in the tool (⋄).

- ⋄ **Studied time frame:** Products in the building envelope have, according to Boverket [26], an expected technical life length of more than 50 years. For product with such a long life time, the calculations are suggested to be done with the reference time of 50 years. This is both because the actual remaining life length of the studied product is deemed difficult to estimate, and because the reference time of 50 years will be in accordance to the proposed climate declarations.
- ⊙ **Product area:** The area of the product is considered easy to inventory while having a direct influence on the result of the assessment. It should thus be entered individually for the specific product being assessed.
- ⊙ **U-value of the old product:** The U-value of the old product is considered to have a significant influence on the result of the assessment. It should thus be entered individually for the specific product being assessed. Specifically for a window however, if this information is not available then the person taking inventory may enter what window type (e.g. 2 glass or 3 glass, and with our without low emission layers) and a U-value that is representative for that window type may then be assigned from a set of values stored in the background system.
- ⋄ **U-value of the new product:** The U-value of the new product might not be known to the person taking inventory, since the choice for what new product that may be used might not be known yet. It may thus be included as an assumption in the background data of the system. We have deemed it reasonable to consider that companies using the CCBuild tool are doing so in order

to lower their climate impact, and therefore assumed that the new product's U-value should be based on the U-values of the most energy efficient products on the market.

- ◇ **Indoor temperature:** The indoor temperature is not a parameter that is considered to have a significant impact on the result. It may thus be included as an assumption in the background calculations. Assuming 20 °C is considered a reasonable estimation since it is within the frame of what the Swedish work environment association considers a good indoor temperature [44].
- ⊙ **Outdoor temperature:** The outdoor temperature does have an influence on the results. It is depending on location, which is easier for the user to input. The location (municipality, etc.) of the building should thus be entered individually for each building being assessed. The site specific temperatures should then be included in the background data of the tool. Here, average monthly data can be used.
- ⊙ **Carbon intensity for district heating:** The carbon intensity of the district heating does have a significant influence of the total result. This, as well, is depending on location, since most municipalities only have one district heating network. The location (e.g. municipality) of the building should thus be entered individually for each building being assessed. For the few municipalities with more than one district heating network, an average carbon intensity for all district heating networks within that municipality may be used, if the specific district heating network can't be found. The average carbon intensity for the district heating network for each municipality in Sweden should then be included in the background data of the tool.

B6 Operational Energy - Appliances

When using the equations in this guideline (presented in appendix H, section H.1.2) in order to calculate the difference in emissions from producing energy that the studied old product would consume compared to a new one, certain data is needed. For the CCBuild valuation tool the following suggestions are made regarding how to handle each parameter needed in order for the calculations to present a result reliable enough for decision making. The parameters in the list are marked with a symbol, representing whether they need product- or case specific input (⊙) or if they can be included as background data in the tool (◇).

- ⊙ **Studied time frame:** The studied time frame has a large influence on the result of the assessment. A dishwasher has a relatively short expected technical service life. As such, the expected remaining technical service life should be calculated for each product being assessed using the year it was purchased, which should be required as an input from the user. The number of years since the purchase should be deducted from an assumed total technical life length, specified for each product type and included in the background data of the tool.
- ◇ **Frequency of use:** The frequency of use of the appliance might have an influence on the results, for appliances which are used momentarily (like a dishwasher) and not continuously (like a refrigerator). However, the actual

frequency of use is impossible to know when the assessment is made. As such it is reasonable to make an assumption included in the background data of the tool, even though the sensitivity analysis has shown that variations might render significantly different results.

- ⊙ **Energy consumption:** The amount of energy consumed per unit of time, e.g. for a year, has a significant impact on the results. It should thus be entered individually for the specific product being assessed, preferably using some easy unit like the energy label of the product. In the EU, each appliance receives a label communicating this energy efficiency. Knowing the energy efficiency of the appliance, one can estimate the amount of energy that will be used in a comparable year. This number can then be used to compare between different products, having made clear which energy efficiency is expected of the new appliance. How the average yearly energy consumption was calculated in the dishwasher case study, and what assumptions were made, is elaborated on in appendix E.
- ⊙ **Product size:** The size of the appliance has shown to affect both the energy consumption, as well as the way that the energy efficiency label is calculated. It should thus be entered individually for the specific product being assessed. Setting the size equal between the new and the existing appliance also makes the results comparable. Either a specific size could be requested, like the specific metric volume of a refrigerator, or one could create different size groups of assumed sizes. This is good if the specific size is hard to know, which implies a risk of getting the wrong input if requiring too much detail. In the dishwasher case study dishwashers were grouped as ”Small” or ”Large”, but if there is a larger range of sizes more steps could be added for increased accuracy.
- ◇ **Carbon intensity for electricity consumption:** The actual carbon intensity from electricity consumption varies all the time, depending on the carbon intensity of the Swedish energy mix, and if or if not electricity is bought from other countries. Since the assessment uses an accounting methodology an average value for the carbon intensity may be assumed. The assumption should be based on that electricity is continuously traded with other countries in northern Europe, such as the carbon intensity assumed in this thesis, in order to account for the electricity that is actually consumed in Sweden and not just produced in Sweden.

B7 Operational Water

When using the equations in this guideline (presented in appendix H section H.1.3) in order to estimate the GHG-emissions associated with water use in an appliance the following parameters should be used. The parameters in the list are marked with a symbol, representing whether they need product- or case specific input (⊙) or if they can be included as background data in the tool (◇).

- ⊙ **Water consumption:** This parameter should be input individually, since it is the one that would distinguish impacts from water consumption between products. However, water consumption has shown to be a very small contributor to the chosen impact category, and variations have in the sensitivity analysis shown to make a small difference in the results. Since this value is also deemed hard to establish for each individual product, we consider it reasonable to assume a water consumption value based on other parameters, such as size or energy label.

- ◇ **Carbon intensity for water pumping and purification:** To use the assumed water consumption to calculate GHG emissions, one should produce a constant representing the emissions caused by energy use from pumping the water to the building and then purifying it once it has been discharged. It is reasonable to use the sum of the average national energy intensities for these two actions, since varying this value has shown in the sensitivity analysis to have only a small effect on the result. This can then be multiplied with the assumed carbon intensity on the Swedish electricity grid.

4.4.3 Reuse phase (Module R)

Within the reuse phase, the processes R1 ”Transport, storage” and R3 ”Transport, reconditioning” (which can be handled in the same way and are thus described jointly below), R2 ”Storage” and R4 ”Reconditioning” should be included where appropriate in the life cycle of the studied products. These processes are a part of the R-module described in the inventory analysis in section 3.2.2, which has been designed in this study to supplement the EN 15978-standard.

R1 ”Transport, storage” & R3 ”Transport, reconditioning”

When using the equations in this guideline (presented in appendix H section H.2.1) in order to estimate the impact from transporting a product in connection to the reuse phase the following parameters should be used. The parameters in the list are marked with a symbol, representing whether they need product- or case specific input (⊙) or if they can be included as background data in the tool (◇).

- ◇ **Type of vehicle:** The type of vehicle used for transport (which determines the amount of emissions per unit of weight and distance), does not have a significant impact on the final result. This parameter value can thus be based on generic assumptions.
- ⊙ **Distance traveled:** The distance traveled does in most cases not have a significant impact on the result of the assessment. Only for a few cases studied in the dishwasher case study, a longer transportation will influence the expected appropriateness of reusing the product. This parameter could thus be included as an assumed value in the background data of the tool. We do, however, recommend that a differentiated assumption is made; the user could then choose to input whether the transportation is e.g. local, regional or national, each representing an assumed distance.
- ◇ **Load factor of vehicle:** The load factor of the vehicle is difficult to foresee, and is not expected to affect the result significantly. It can thus be included as an assumption in the background data.
- ◇ **Product weight:** The weight of the product influences the GHG emissions associated with transportation, however not enough to make a significant im-

pact on the result. In order to facilitate calculating transportation emissions it is recommended to assume a product specific weight in the data of the background system. This assumed weight can, for e.g. building envelope products, be calculated using a conversion factor for the area of the product which can be found in Boverket's database. They can also be based on generic assumptions regarding a standard version of the studied product.

R2 Storage

When using the equations in this guideline (presented in appendix H section H.2.2) in order to estimate the impact from storage in connection to the reuse phase, certain data is needed. The parameters in the list are marked with a symbol, representing whether they need product- or case specific input (⊙) or if they can be included as background data in the tool (◇).

⊙ **Storage time:** The duration of the storage directly impacts the emissions allocated towards the product. These emissions might affect the results of the assessment to some extent, as seen in the sensitivity analysis. Since the duration of storage might be hard to know when the assessment is made, an assumption should be included in the background data of the system; however, the user should also be given the option to enter an estimate if they see fit. This could increase the accuracy of the result.

◇ **Carbon intensity of storage:** The amount of emissions that should be allocated towards the product depend on many parameters; energy use in the facility, carbon intensity of the different energy types used, size of the facility, fill rate, etc. This is considered hard to establish for the user, while affecting the result only a small amount, and should as such be included as an assumption in the background data.

R4 Reconditioning

In general terms what is analysed in this process is how much emissions that reconditioning of the old product, in order for it to be reused, would cause. Specifically, we have calculated these emissions for exchanging a faulty or insufficiently performing part. The suggested formula for this calculation is presented in appendix H section H.2.3. If no data for the emissions from producing a new part can be found, the impact from the reconditioning process may be calculated as a percentage share of the emissions from the A module relative to the weight percentage of the exchanged part of the product. This would then have to be communicated to be an estimation of the impact. The impact from parameters such as cleaning and painting were concluded to be small enough to be omitted.

In order to facilitate the use of the CCBuild tool, the suggestion is made that the user only need to enter whether or not certain parts of the product will be exchanged for new parts. Assumptions therefore has to be made by the tool developer regarding which parts of a product that may be considered for reconditioning for different product types, and should thus be included in the background data.

5

Discussion

The aim of this study has been to investigate how the effect of reuse on total life cycle emissions can be assessed. The focus has been on products considered interesting in renovation projects, particularly looking at emissions from energy use during the use phase and from processes connected to enabling reuse, or the ”reuse phase”. In this chapter we will discuss the results and findings of the study, what aspects have been successful, which aspect are lacking, and what we have learned.

The model

As was expected in the beginning of the study, we have seen that emissions from the use phase (module B) can have an extensive impact on the potential greenhouse gas savings from reusing certain products. Neglecting to include these activities in tools like the one provided by CCBuild could thus potentially result in misleading results being used as a basis for decision making, leading to greater emissions than expected across the life cycle. We have also seen that it is possible to produce an estimation of the net effect on greenhouse gas emissions for the entire life cycle of a product, even with little information available. This has several implications; assessments with a more holistic result can be provided to the user, while still leaving the tool easy to use, as well as letting a person conduct assessments without much prior knowledge about LCA. Still, the inputs asked for gives the assessment an individualized touch, allowing to take certain product specific conditions into consideration. These assessments can then also be conducted using a small amount of time per product, which is important in order for the assessments to actually be made.

To achieve this has required making many assumptions. Even though we think that these assumptions are well founded, an effect of this is that the result from the assessment is rather uncertain. This affects the reliability of the results, meaning that the exact value of the result provided by this assessment can not be said to represent the actual net effect on emissions. This may be seen as a weakness of the guideline, but as mentioned previously, the aim of the calculations are to be used as a basis for decision making and not for calculating exact greenhouse gas emissions. Since the emissions calculated in the assessment all lie in the future, and depend on how the product is used, calculating an exact result can be said to be impossible. Therefore, we think that this model, although showing uncertainties in several parameters, provides a useful tool for estimating and comparing the scale of the net effects from reuse on the life cycle emissions of a product, in an environment where exact calculations are not available.

With regards to uncertainties, there are two further interesting aspects to consider. The first one is that in a sensitivity analysis, only the variation in one parameter is tested at a time. This means that we only see the results for if a change would occur in one parameter, while all other remain as assumed in the original calculation. However, in reality it is likely that multiple parameters vary simultaneously. This may lead to a larger deviation from the original results than is observed in the sensitivity analyses.

The second one is that when assessing a single individual product, the deviation of it's characteristics from the assumed parameter values embedded in the system might be significant, producing a somewhat misleading result. However, when assessing multiple products of the same kind, some parameters will differ between them; an example would be the need for repair in a set of windows. If several windows have a different need for repair, then the mean value of their need for repair might be closer to the assumptions used in the calculations than that of a single window. Thus, we believe that some assumed parameters, while possibly misrepresenting some products individually, will produce better results for a larger set of products.

The model presented in this thesis will not be compatible with the Swedish climate declarations, proposed to be introduced in the beginning of 2022. As stated in section 2.3.2 the climate declarations will then only account for processes in module A [25]. However, as also stated in section 2.3.2, processes from module B and C are proposed by Boverket to be included in the declarations from 2027. If this is implemented then the model declarations will be more in line with the model presented in this study. The purpose of the CCBuild tool and the climate declarations will nevertheless still differ, were the earlier aims to visualize the total net emissions from reusing specific products, while the later aims to visualize the total climate impact from a building. We still hope that some of the findings in this thesis might be helpful in developing models for calculating future variations of the climate declarations, to incorporate the life cycle perspective.

As discussed in section 3.2.2 the carbon intensity from district heating networks differ quite significantly between the networks in Sweden [38]. This was found to influence the appropriateness of reusing a certain product in certain locations. When modelling these assessments, we have successfully incorporated local conditions, both in terms of the carbon intensity of district heating and local temperatures. These aspects have shown to make reuse of a window beneficial in certain parts of Sweden, but not in others. We have, in doing this, shown that we can provide more relevant results from analysing larger data sets. This could perhaps be used to increase the accuracy of calculations in other parts of the model, like the energy use in specific locations like storage facilities or water treatment. The same level of location specificity is not possible with the carbon intensity of the electricity mix, since this a lot more centralized, and causal relationships between production and consumption is harder to determine. However, it might be possible in the future to allow entering certain building specific data; if e.g. the house has roof-mounted solar panels, these could then be assumed to cover a certain share of the electricity consumption of each product. This could create a more location-specific assessment also with regards to electricity.

Uncertainties regarding technology development

One aspect that is not accounted for in our assessment, is the future developments of both district heating and electricity production. Changes to the carbon intensity on these grids could change the outcome of the assessments quite drastically. In order to not overestimate the potential emissions savings from reuse, we have in this report assumed that the electricity- and district heating grids with retain their current carbon intensity during the course of the case study time periods. This especially has an impact on the results from assessments accounting for a longer time span, like the case of the window. Based on the facts that the greenhouse gas emission intensity of the electricity generation in Europe was 47% lower in 2019 than in 1990 [51], and that the EU has proposed a goal to reduce the net greenhouse gas emissions from the member countries with at least 55% compared to the 1990 levels by 2030 [52], the carbon intensity of energy consumption will hopefully continue to decrease for both energy types. This type of improvements are not possible to correctly integrate in the calculations, but practitioners may simply keep in mind that if studying products with a long life span, the benefits from reuse can be larger than estimated.

We did in the case studies make the choice of assuming that the new product in each comparison is of the highest possible energy efficiency. This assumption is based on the values for current products; if (or when) new products become even more energy efficient in the future, the relevant adjustments can be made to the background data of the tool to account for that.

If the development of energy production continue in the right direction, then the impact from the use phase (module B) would not be as dominating when calculating the climate impact of a product. Other life cycle phases could then turn out to be more important for the assessment results. Therefore, the reuse module proposed in this study might be more significant in the future. It is thus appropriate to incorporate it right now, to learn how it influences results, and to better adapt it in the future when it might be deemed appropriate to use more detailed or case specific inventory data for it's processes.

User interaction

This study has not in particular investigated how humans will interact with the tool. This is another aspect that motivates taking in only a few customized parameters from the user - the uncertainties in how a user interprets each input opens up for more variations in the results, when different users routinely fill in forms in different ways. Some information could also be considered too tedious to extract for each individual product. On the other hand, if it is done correctly and users are willing to spend more time on the inventory process, a more accurate result could be generated.

To open up for the benefits of higher detail where it is possible, one could work with two different types of settings; *optional inputs* and *pre-determined assumptions.* While some parameters values are mandatory to enter, some inputs could be optional; if no value is entered, an assumption stored in the background data is used. This might lead to a higher level of detail in some assessments. However, if the level of detail varies in between assessments, this could affect the trustworthiness of the results of the tool in general. Pre-determined assumptions would be another way of receiving input; instead of asking the user for the distance and transportation mode to the storage, the user could be asked to choose between e.g. ”Local”, ”Regional” or ”National” transport, all implying certain assumptions for these parameters.
One way of informing the user of the accuracy of the results, especially if different levels of detailed is allowed, could be to visualise this with e.g. a percentage or color. Since different products have different processes connected to their life cycles, and the different processes require different amounts of assumptions in relation to the case specific values, the level of accuracy of the result will vary. The results for product which do not have any use phase emissions will for instance be more accurate than for product with use phase emissions. This is simply because a lot of assumptions are needed in order to calculate the climate impact from the use phase, especially since it implies making assumptions about the future. If the user chooses to enter more product specific data this will also generate a more accurate results. Perhaps, if the level of accuracy would be communicated by e.g. a colour ranging from green to red with increasing level of uncertainty, the user could know more about the context of the results, making the tool more trustworthy.

6

Conclusion

This thesis used an inductive method to analyse how prospective emissions from the use- and reuse phases can be taken into account when calculating the difference in environmental impact between reusing a product and buying a new one, using two accounting LCAs. This in order to facilitate the development of the CCBuild platform and the value analysis tool provided in this platform. The thesis resulted in a guideline for how such comparative life cycle assessments can be conducted.

One of the key findings in this thesis are that the use- and reuse phase emissions might have a considerable impact on the life cycle emissions of a product, affecting it's appropriateness to be reused. Another key finding is that different parameters will have different amount of influence on the results, and can therefore be attended to with different levels of detail. This allows letting the tool developer decide which parameters should be required as input from the user.

Having the CCBuild tool take the entire life cycle into account will generate a result that is more representative of reality in terms of visualizing the net effect on greenhouse gas emissions that reuse can have, which prevents sub-optimizing systems. The guideline developed in this thesis uses LCA to account for the entire life cycle, which has shown potential to provide a good basis for decisions, as also seen in previous studies [9] [10]. The model is easy to use (after having been embedded into the system) which might make it possible to implement within the construction industry and thus increase knowledge of the consequences of certain actions, which is one important method for transitioning their business model [8].

For future studies, we recommend that this model is tried and implemented for more products and product types, drawing on the experiences gathered in this thesis. This would evaluate if it is possible to conduct this type of assessments on a larger scale. Furthermore, we recommend that these studies include the user perspective of what inputs to the calculations can be required, and how the interface should be designed so as to promote relevant inputs while still being easy to use. We also recommend studying how the results can be presented so as to communicate the level of uncertainty in the calculations, to provide the user with a relevant foundation for decisions.

Our hope is that stakeholders within the construction industry will, with the help of the CCBuild platform and tool, make the best possible decisions regarding the sourcing of building materials, promoting informed decisions in the transition towards circularity.

Bibliography

[1] Naturvårdsverket, "BYGGBRANSCHEN," Återvinningsenheten, Naturvårdsverket, Tech. Rep., 2020, p. 2. [Online]. Available: `https://www.naturvardsverket.se/upload/sa-mar-miljon/mark/avfall/statistikblad/avfall-statistikblad-byggbranschen.pdf`.

[2] ——, *Avfall i Sverige 2016.* 2018, pp. 1–112, ISBN: 978-91-620-6839-4. [Online]. Available: `www.naturvardsverket.se/publikationer`.

[3] S. O. Ajayi, L. O. Oyedele, M. Bilal, O. O. Akinade, H. A. Alaka, H. A. Owolabi, and K. O. Kadiri, "Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements," *Resources, Conservation and Recycling*, vol. 102, 2015, ISSN: 18790658. DOI: `10.1016/j.resconrec.2015.06.001`.

[4] C. M. Rose and J. A. Stegemann, "From waste management to component management in the construction industry," *Sustainability (Switzerland)*, vol. 10, no. 1, 2018, ISSN: 20711050. DOI: `10.3390/su10010229`.

[5] International Energy Agency, "Global Status Report for Buildings and Construction 2019," *International Energy Agency*, 2019.

[6] K. T. Adams, M. Osmani, T. Thorpe, and J. Thornback, "Circular economy in construction: Current awareness, challenges and enablers," in *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, vol. 170, 2017. DOI: `10.1680/jwarm.16.00011`.

[7] J. Hart, K. Adams, J. Giesekam, D. D. Tingley, and F. Pomponi, "Barriers and drivers in a circular economy: The case of the built environment," in *Procedia CIRP*, vol. 80, 2019. DOI: `10.1016/j.procir.2018.12.015`.

[8] H. Gerhardsson, C. L. Lindholm, J. Andersson, A. Kronberg, M. Wennesjö, and F. Shadram, "Transitioning the Swedish building sector toward reuse and circularity," *IOP Conference Series: Earth and Environmental Science*, vol. 588, no. 4, 2020, ISSN: 17551315. DOI: `10.1088/1755-1315/588/4/042036`.

[9] O. Ortiz, F. Castells, and G. Sonnemann, *Sustainability in the construction industry: A review of recent developments based on LCA*, Jan. 2009. DOI: `10.1016/j.conbuildmat.2007.11.012`.

[10] X. Oregi, P. Hernandez, C. Gazulla, and M. Isasa, "Integrating simplified and full life cycle approaches in decision making for building energy refurbishment: Benefits and Barriers," *Buildings*, vol. 5, no. 2, 2015, ISSN: 20755309. DOI: `10.3390/buildings5020354`.

[11] CCBuild, *Metod för värdeanalys av återbruk.* [Online]. Available: `https://ccbuild.se/sv/marknadsplats/hjalp`.

[12] ——, *Om oss.* [Online]. Available: `https://ccbuild.se/om-oss/`.

[13] K. Hartley, R. van Santen, and J. Kirchherr, "Policies for transitioning towards a circular economy: Expectations from the European Union (EU)," *Resources, Conservation and Recycling*, vol. 155, 2020, ISSN: 18790658. DOI: `10.1016/j.resconrec.2019.104634`.

[14] R. Merli, M. Preziosi, and A. Acampora, *How do scholars approach the circular economy? A systematic literature review*, 2018. DOI: `10.1016/j.jclepro.2017.12.112`.

[15] The Ellen MacArthur Foundation, "Towards a Circular Economy - Economic and Business Rationale for an Accelerated Transition," *Greener Management International*, 2012, ISSN: 10881980.

[16] B. A. Andersson and I. Råde, "Material constraints on technology evolution: The case of scarce metals and emerging energy technologies," in *A Handbook of Industrial Ecology*, 2002, pp. 391–404, ISBN: 9781840645064. DOI: `https://doi.org/10.4337/9781843765479.00043`.

[17] R. Dietz and D. O'Neill, "PART II : STRATEGIES OF ENOUGH chapter 5. Enough Throughput," in *Enough Is Enough*, 2013. DOI: `10.4324/9780203441121-13`.

[18] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, and E. Worrell, *Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics*, 2019. DOI: `10.1016/j.resconrec.2019.104498`.

[19] European Parliament and Council European, "Directive 2008/98/EC on waste (Waste Framework Directive) - Environment - European Commission," *Official Journal of the European Union*, vol. 312, 2008.

[20] E. Schut, M. Crielaard, and M. Mesman, "Circular economy in the Dutch construction sector," *Rijkswaterstaat - National Institute for Public Health and the Environment*, no. December, pp. 1–58, 2015.

[21] Circle Economy, *The Circularity Gap Report: Our World is only 9% Circular – Circle Economy*, 2018.

[22] H. Baumann and A.-M. Tillman, *The Hitch Hiker's Guide to LCA*. 2004.

[23] ISO, "14040: Environmental management–life cycle assessment—Principles and framework," *International organization for standardization*, 2006.

[24] H. Gerhardsson, J. Andersson, and Å. Thrysin, " Återbrukets klimateffekter vid byggnation Handledning för klimatberäkningar i enlighet med EN 15978," Tech. Rep., 2020. [Online]. Available: `https://www.ivl.se/download/18.72fab6cc1761c7ad2941478/1607947586855/C562.pdf`.

[25] Boverket, "Utveckling av regler om klimatdeklaration av byggnader," Tech. Rep., 2020. [Online]. Available: `https://www.boverket.se/globalassets/publikationer/dokument/2020/utveckling-av-regler-om-klimatdeklaration-av-byggnader.pdf`.

[26] ——, *Boverkets klimatdatabas.* [Online]. Available: `https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/klimatdatabas/`.

[27] L. Hebert, J. Green, P. Newman, R. Minnuno, and F. Geromino, "Environmental sustainability of prefabricated modular residential buildings compared

to traditional equivalent: two case studies in Perth, Australia," in *7th International Conference on Energy and Environment of Residential Buildings*, 2016.

[28] EN 15978, "BS EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method," *International Standard*, no. November, 2011.

[29] V. Hasik, E. Escott, R. Bates, S. Carlisle, B. Faircloth, and M. M. Bilec, "Comparative whole-building life cycle assessment of renovation and new construction," *Building and Environment*, vol. 161, 2019, ISSN: 03601323. DOI: `10.1016/j.buildenv.2019.106218`.

[30] A. Vilches, A. Garcia-Martinez, and B. Sanchez-Montañes, *Life cycle assessment (LCA) of building refurbishment: A literature review*, 2017. DOI: `10.1016/j.enbuild.2016.11.042`.

[31] A. Rønning, M. Vold, and G. Nereng, "Refurbishment or Replacement of Buildings – What is Best for the Climate ?" *Joint Actions on Climate Change*, no. April, 2009.

[32] Preservation Green Lab, "The Greenest Building : Quantifying the Environmental Value of Building Reuse," pp. 1–94, 2011.

[33] F. Ardente, M. Beccali, M. Cellura, and M. Mistretta, *Energy and environmental benefits in public buildings as a result of retrofit actions*, 2011. DOI: `10.1016/j.rser.2010.09.022`.

[34] M. J. Yan, J. Humphreys, and N. M. Holden, "Evaluation of process and input-output-based life-cycle assessment of Irish milk production," *Journal of Agricultural Science*, vol. 151, no. 5, pp. 701–713, Oct. 2013, ISSN: 00218596. DOI: `10.1017/S0021859613000257`. [Online]. Available: `https://doi.org/10.1017/S0021859613000257`.

[35] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, *Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review*, 2014. DOI: `10.1016/j.rser.2013.08.037`.

[36] P. Hopkinson, H. M. Chen, K. Zhou, Y. Wang, and D. Lam, "Recovery and reuse of structural products from end-of-life buildings," *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, vol. 172, no. 3, 2018, ISSN: 17517680. DOI: `10.1680/jensu.18.00007`.

[37] D. Densley Tingley and B. Davison, "Developing an LCA methodology to account for the environmental benefits of design for deconstruction," *Building and Environment*, vol. 57, 2012, ISSN: 03601323. DOI: `10.1016/j.buildenv.2012.06.005`.

[38] R. Khodayari, *Miljövärdering av fjärrvärme*, 2020. [Online]. Available: `https://www.energiforetagen.se/statistik/fjarrvarmestatistik/miljovardering-av-fjarrvarme/`.

[39] F. Ardente and L. Talens Peiró, *Report on benefits and impacts/costs of options for different potential material efficiency requirements for Dishwashers*, March. 2015, ISBN: 978-92-79-47484-2. DOI: `10.2788/720546`. [Online]. Available: `https://ec.europa.eu/jrc`.

[40] P. Tecchio, F. Ardente, and F. Mathieux, "Understanding lifetimes and failure modes of defective washing machines and dishwashers," *Journal of Cleaner*

Production, vol. 215, 2019, ISSN: 09596526. DOI: `10.1016/j.jclepro.2019.01.044`.

[41] K. Laitala, I. G. Klepp, V. Haugrønning, H. Throne-Holst, and P. Strandbakken, "Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry," *Journal of Cleaner Production*, vol. 282, 2021, ISSN: 09596526. DOI: `10.1016/j.jclepro.2020.125349`.

[42] Daneby Glas AB, "BYT GLAS ISTÄLLET FÖR FÖNSTER," Tech. Rep. [Online]. Available: `https://danebyglas.se/wp-content/uploads/2018/06/GLASBYTE_KATALOG.pdf`.

[43] Energimyndigheten, "Fönsterrenovering med energiglas," Tech. Rep., 2006. [Online]. Available: `https://www.gbf.se/sites/default/files/files/fonsterrenovering(www).pdf`.

[44] Arbetsmiljöverket, *Temperatur och klimat*, Mar. 2021. [Online]. Available: `https://www.av.se/inomhusmiljo/temperatur-och-klimat/`.

[45] A. Boyano, H. Moons, A. Villanueva, K. Graulich, I. Rüdenauer, F. Alborzi, I. Hook, and R. Stamminger, *Ecodesign and energy label for household dishwashers*. 2017, pp. 1–716, ISBN: 9789279741852.

[46] A. Moro and L. Lonza, "Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles," *Transportation Research Part D: Transport and Environment*, vol. 64, 2018, ISSN: 13619209. DOI: `10.1016/j.trd.2017.07.012`.

[47] A. Lingsten, M. Lundkvist, and D. Hellström, "VA-verkens energianvändning 2011," *Svenskt Vatten Utveckling*, 2011.

[48] Svenska Fönster AB, "ENVIRONMENTAL PRODUCT DECLARATION," Tech. Rep., Apr. 2020. [Online]. Available: `https://portal.environdec.com/api/api/v1/EPDLibrary/Files/91db9ee3-87b6-4d1f-95a3-9381d55189eb/Data`.

[49] Network for Transport Measures, *Road cargo transport baselines 2020 EU*. [Online]. Available: `https://www.transportmeasures.org/en/wiki/evaluation-transport-suppliers/road-transport-baselines-2020/`.

[50] D. Avasoo, "Effektiva fönster - en bra investering," *Vi i villa*, 2003. [Online]. Available: `https://www.viivilla.se/gor-det-sjalv/fonster--dorrar-1/effektiva-fonster-en-bra-investering1/`.

[51] European Environment Agency, *Greenhouse gas emission intensity of electricity generation*, 2020. [Online]. Available: `https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111`.

[52] European Commissions, *2030 climate & energy framework*. [Online]. Available: `https://ec.europa.eu/clima/policies/strategies/2030_en`.

A

Flowchart - Dishwasher case study

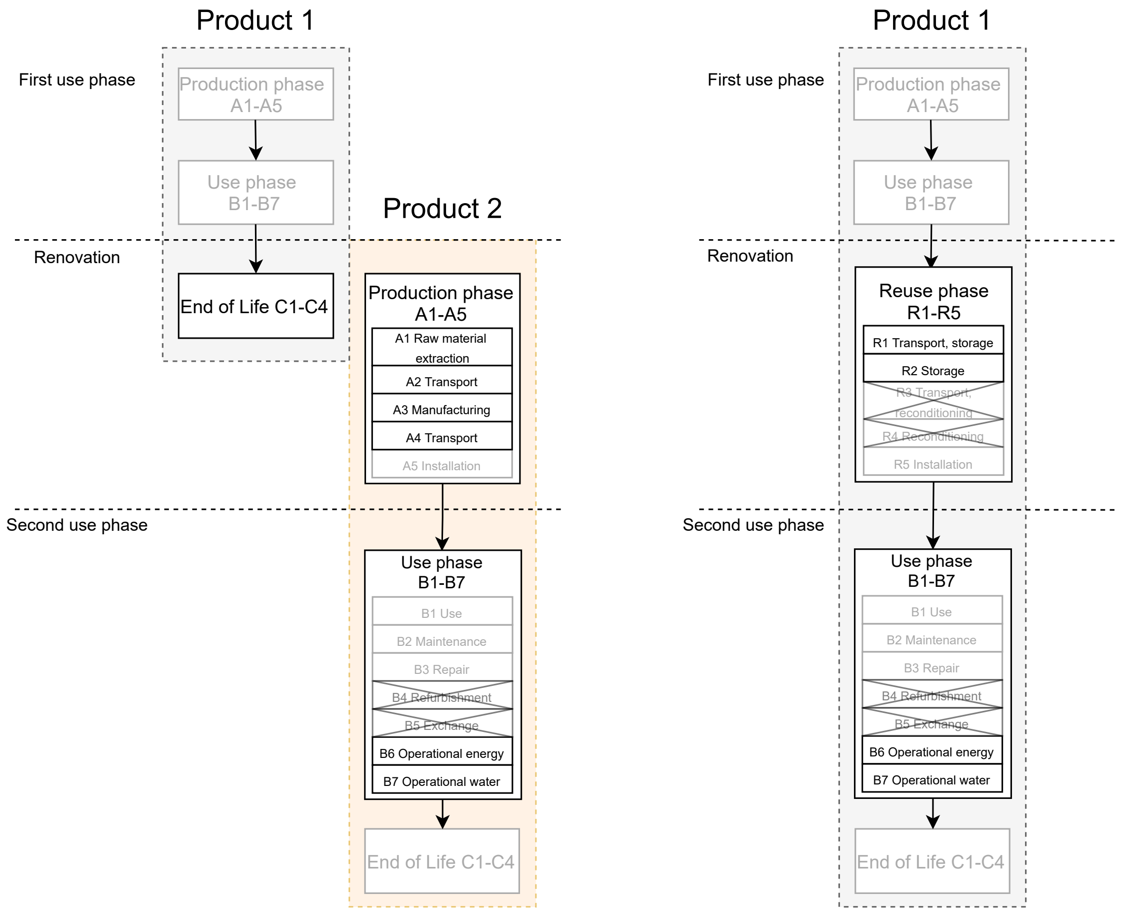


Figure A.1: The two life cycle options for sourcing a dishwasher. To the left, the linear option where a new product replaces the existing product. To the right, the circular option where the existing product is reused. Grey boxes are deemed equal between the two systems and omitted from the comparison; crossed out boxes are deemed outside of the scope irrelevant to the study.

B

Flowchart - Window case study

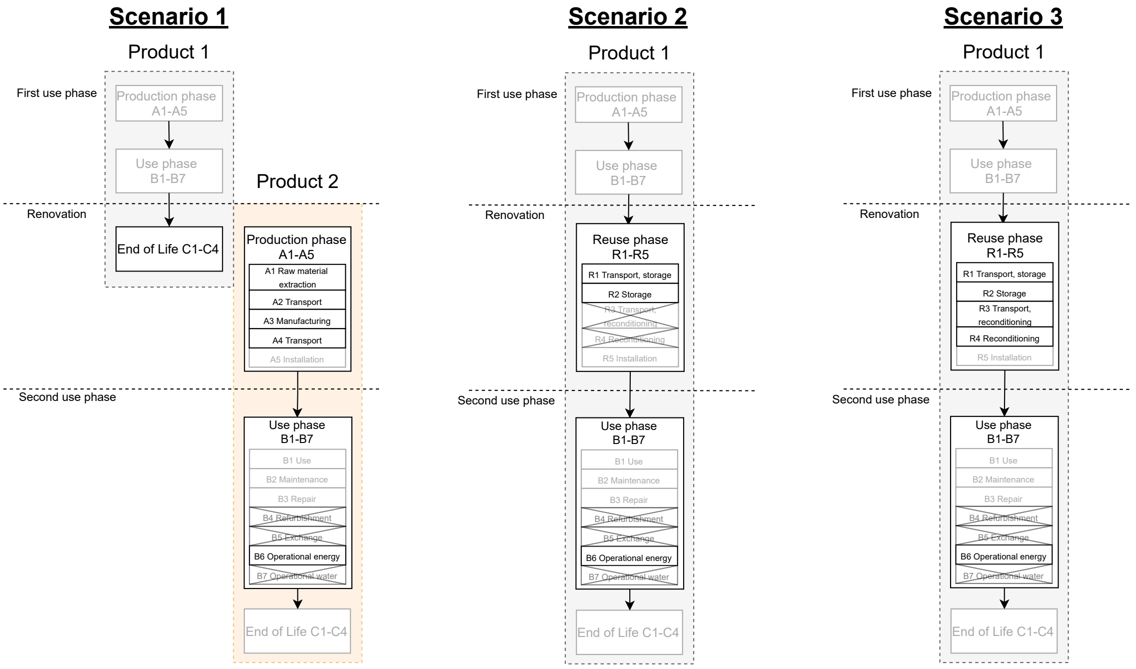


Figure B.1: The three life cycle options for sourcing a dishwasher studied in this assessment. To the left, the linear scenario where a new product replaces the existing product. In the middle, the first circular scenario where the existing product is reused. To the left, the second circular scenario where the existing product is reconditioned before being reused. Grey boxes are deemed equal between the three systems and omitted from the comparison; crossed out boxes are deemed outside of the scope irrelevant to the study.

C

Calculations - Window case study

Emissions have been calculated for each module in the products life cycle separately. The variables representing the total emissions from each module are presented in table C.1 connected The final calculations of the difference in climate impact between scenario 1 and scenario 2, as well as between scenario 1 and scenario 3 are calculated by subtracting the total climate impact from the studied processes in scenario 2 and 3 from the total climate impact from the studied processes in scenario 1 respectively (see equation C.1 and C.2).

Table C.1: Variables for emissions from different life cycle stages

	Module A	Module B	Module R	Module C
Scenario 1	X_A	$X_{B:Sc1}$	-	X_C
Scenario 2	-	$X_{B:Sc2}$	$X_{R:Sc2}$	-
Scenario 3	-	$X_{B:Sc3}$	$X_{R:Sc3}$	-

$$\Delta X_{1-2} = (X_A + X_{B:Sc1} + X_C) - (X_{R:Sc2} + X_{B:Sc2}) \tag{C.1}$$

$$\Delta X_{1-3} = (X_A + X_{B:Sc1} + X_C) - (X_{R:Sc3} + X_{B:Sc3}) \tag{C.2}$$

Emissions from each process will be referred to as $X_{B6:Sc1}$ etc.

Emissions from module A and C have been gatherer from external sources and are presented in table C.2. Calculations of emissions from module B and R will be presented in the following sections.

Table C.2: Assumed values for the life cycle emissions variables, for module A and C. Given in kg CO_2-eq

	3-glass wooden window
X_A	94.68
X_C	5.81

C.1 Module B calculations

The only process included in the use phase is B6 Operational energy, meaning that;

$$X_{B:Sc1} = X_{B6:Sc1} \tag{C.3}$$

$$X_{B:Sc1} = X_{B6:Sc2} \tag{C.4}$$

$$X_{B:Sc3} = X_{B6:Sc3} \tag{C.5}$$

C.1.1 B6 Operational Energy

The following formulas were used in order to calculate the impact from process B6 Operational Energy;

$$X_{B6} = Q \cdot C_{heat} \cdot t_{year} \tag{C.6}$$

$$Q = A \cdot U \cdot (T_{in} - T_{out}) \tag{C.7}$$

Table C.3: All parameters used in calculations for B6 Operational Energy

Parameter	**Variable**	**Assumed value**
Carbon Intensity from district heating	C_{heat}	See table C.4
Studied time frame	t	50 years
Energy transmitted through window	Q	-
Window area	A	1.5 m^2
Window U-value	U	See table C.5
Inside temperature	T_{in}	20 ° C
Outside temperature	T_{out}	Hourly temperatures during 2019 for all studied locations (retrieved from SMHI)

Table C.4: Carbon intensity from analysed district heating companies, in CO_2-eq emissions per delivered kWh of district heating. Gathered from [38]

Location	*District heating company*	*Emissions, C_{heat} [kg CO_2-eq/kWh]*
Stockholm	Stockholm Exergi	0.065
Linköping	Tekniska Verken	0.103
Kungsbacka	Statskraft Värme	0.012

Table C.5: U-values used for calculations for the different window types and scenarios, in W/m^2·K.

	2-glass window	2+1-glass window	3-glass window
Scenario 1	-	-	1.0
Scenario 2	2.8	1.8	-
Scenario 3	1.2	1.0	-

Calculations were done for all different U-values in all locations, generating three different values for $X_{B6:Sc1}$ and six different values for $X_{B6:Sc2}$ and $X_{B6:Sc2}$ respectively.

C.2 Module R calculations

The processes included from this module varies in the two circular scenarios. In scenario 2 process R1 and R2 are included while in scenario 3 process R4 and R5 are also included. This gives that;

$$X_{R:Sc2} = X_{R1:Sc2} + X_{R2:Sc2} \tag{C.8}$$

$$X_{R:Sc3} = X_{R1:Sc3} + X_{R2:Sc3} + X_{R3:Sc3} + X_{R4:Sc3} \tag{C.9}$$

C.2.1 R1 & R3 Transport

The following formula was used in order to calculate the impact from process R1 and R3 Transport;

$$X_{R1}, X_{R3} = C_{transp} \cdot d \cdot m \tag{C.10}$$

Table C.6: All parameters used in calculations for R1 & R3 Transport

Parameter	Variable	Assumed value
Distance	d	200 km
Type of vehicle	-	Light duty vehicle
Loading factor	-	0.4
Carbon intensity from transport	C_{transp}	0.557 kg CO_2-eq/ton·km
Weight	m	A·CF
Weight Conversion factor	CF	35.3 kg/m^2 (retrieved from Boverket)

C.2.2 R2 Storage

The following formula was used in order to calculate the impact from process R1 and R3 Transport;

$$X_{R2} = \frac{C_{elec} \cdot Q_{elec/year} + C_{heat} \cdot Q_{heat/year}}{n_s \cdot Ffill} \cdot A_{floor} \cdot t_{storage} \tag{C.11}$$

Table C.7: All parameters used in calculations for R2 Storage

Parameter	**Variable**	**Assumed value**
Storage unit area	$\mathrm{A}_{storage}$	800 m^2
Number of shelf levels	n_s	3
Fill rate	F_{fill}	0.8
Storage time	$\mathrm{t}_{storage}$	6 months
Covered floor area per window	A_{floor}	0.3 m^2
Storage yearly electricity consumption	$\mathrm{Q}_{elec/year}$	69.28 $\mathrm{kWh/m}^2$
Storage yearly heating consumption	$\mathrm{Q}_{heat/year}$	280 $\mathrm{kWh/m}^2$
Carbon intensity from electricity consumption	C_{elec}	0.047 kg CO^2/kWh
Carbon intensity from district heating	C_{heat}	0.074 kg CO^2/kWh

C.2.3 R4 Reconditioning

$$X_{R4} = X_{recond} + X_{EoL:glass} + X_{paint} + X_{cleaning} \tag{C.12}$$

$\mathrm{X}_{EoL:glass}$, X_{paint} and $\mathrm{X}_{cleaning}$ were all neglected because of their small impacts, giving that;

$$X_{R4} = X_{recond} \tag{C.13}$$

$$X_{recond} = X_{isoglass} \cdot A \tag{C.14}$$

Table C.8: All parameters used in calculations for R4 Reconditioning

Parameter	**Variable**	**Assumed value**
Climate impact from producing an isolation glass cassette	$\mathrm{X}_{isoglass}$	35 kg CO_2-eq/m^2
Window area	A	1.5 m^2

D

Calculations - Dishwasher case study

Emissions have been calculated for each module in the products life cycle separately. The variables representing the total emissions from each module are presented in table D.1. The final calculations of the difference in climate impact between the linear and the circular scenario are calculated by subtracting the total climate impact from the studied processes in the circular scenario from the total climate impact from the studied processes in the linear scenario (see equation D.1).

Table D.1: Variables for emissions from different life cycle stages

	Module A	Module B	Module R	Module C
Linear option	X_A	$X_{B,new}$	-	X_C
Circular option	-	$X_{B,old}$	X_R	-

$$\Delta X = \frac{t}{t_{service}} \cdot (X_A + X_C) + X_{B:new} - (X_{R:old} + X_{B:old}) \tag{D.1}$$

t is the remaining expected service time of the older dishwasher; $t_{service}$ is the total expected service life of a new dishwasher. In this study, the assumeption is $t_{service} = 12.5$, as per [40].

Emissions from each process, included in the modules, will be referred to as $X_{B6:new}$ etc.

Emissions from module A and C have been gathered from external sources and are presented in table D.2. Calculations of emissions from module B and R will be presented in the following sections.

Table D.2: Assumed values for the life cycle emissions variables, for module A and C. Given in kg CO_2-eq

	Small dishwasher	Large dishwasher
X_A	127.5	153
X_C	6.2	6.2

D.1 Module B calculations

The only processes included in the use phase are B6 Operational energy and B7 Operational water, meaning that;

$$X_{B:new} = X_{B6:new} + X_{B7:new} \tag{D.2}$$

$$X_{B:old} = X_{B6:old} + X_{B7:old} \tag{D.3}$$

D.1.1 B6 Operational Energy

The following formulae was used in order to calculate the impact from process B6 Operational Energy;

$$X_{B6:new} = C_{elec} \cdot E_{new} \cdot t \tag{D.4}$$

$$X_{B6:old} = C_{elec} \cdot E_{old} \cdot t \tag{D.5}$$

The new dishwasher is always assumed to have energy label A+++.

Table D.3: All parameters used in calculations for B6 Operational Energy, for a dishwasher or a similar appliance. t is calculated based on the year of purchasing the appliance.

Parameter	**Variable**	**Assumed value**
Carbon intensity from electricity consumption	C_{elec}	0.47 kg CO_2/kWh
Annual energy use of a dishwasher	$E_{new/old}$	See table D.4
Number of expected remaining years of service for the older appliance	t	0.5-12.5 years
Average expected lifetime of a dishwasher	$t_{service}$	12.5 years

Table D.4: Assumed annual energy use of an arbitrary dishwasher, small or large. Based on calculations presented in appendix E.

Energy label	Small	Large
A+++	176.4	234.5
A++	194.04	257.95
A+	218.74	290.78
A	246.96	328.3
B	278.71	370.51

D.1.2 B7 Operational Water

The following formula was used in order to calculate the impact from process B7 Operational Water;

$$X_{B7:new} = C_{elec} \cdot E_{water-elec} \cdot V_{new} \cdot W \cdot t \tag{D.6}$$

$$X_{B7:old} = C_{elec} \cdot E_{water-elec} \cdot V_{old} \cdot W \cdot t \tag{D.7}$$

The new dishwasher is always assumed to have energy label A+++.

Table D.5: All parameters used in calculations for B7 Operational Water

Parameter	**Variable**	**Assumed value**
Carbon intensity from electricity consumption	C_{elec}	0.47 kg CO_2/kWh
Water use per washing cycle of a dishwasher	V	See table D.6
Energy consumption from water use	$E_{water-elec}$	1.67 kWh/m^3
Wash cycles per year	W	280
Number of expected remaining years of service for the older appliance	t	0.5-12.5 years

Table D.6: Assumed number of liters of water consumed per washing cycle for different energy labels

EC	Liters per dishwashing cycle
A+++	9
A++	10
A+	11
A	12
B	13

D.2 Module R calculations

The processes included from this module are R1 Transport and R2 Storage. This gives that;

$$X_R = X_{R1:Sc2} + X_{R2:Sc2} \tag{D.8}$$

D.2.1 R1 Transport

The following formula was used in order to calculate the impact from process R1 Transport;

$$X_{R1} = C_{transp} \cdot d \cdot m \tag{D.9}$$

Table D.7: All parameters used in calculations for R1 Transport

Parameter	**Variable**	**Assumed value**
Distance	d	200 km
Type of vehicle	-	Light duty vehicle
Loading factor	-	0.4
Carbon intensity from transport	C_{transp}	0.557 kg CO_2-eq/ton·km
Weight	m	Small: 40 kg Large: 48 kg

D.2.2 R2 Storage

The following formula was used in order to calculate the impact from process R1 and R3 Transport;

$$X_{R2} = \frac{C_{elec} \cdot Q_{elec/year} + C_{heat} \cdot Q_{heat/year}}{n_s \cdot F_{fill}} \cdot A_{floor} \cdot t_{storage} \tag{D.10}$$

Table D.8: All parameters used in calculations for R2 Storage

Parameter	**Variable**	**Assumed value**
Storage unit area	$\mathrm{A}_{storage}$	800 m^2
Number of shelf levels	n_s	3
Fill rate	C_{fill}	0.8
Storage time	$\mathrm{t}_{storage}$	6 months
Covered floor area per window	A_{floor}	1 m^2
Storage yearly electricity consumption	$\mathrm{Q}_{elec/year}$	69.28 kWh/m^2
Storage yearly heating consumption	$\mathrm{Q}_{heat/year}$	280 kWh/m^2
Carbon intensity from electricity consumption	C_{elec}	0.047 kg CO^2/kWh
Carbon intensity from district heating	C_{heat}	0.074 kg CO^2/kWh

E

Calculating the annual energy use of a dishwasher

In this appendix we demonstrate how we have calculated the annual energy use of a dishwasher, using it's energy label.

We use the energy labelling system in effect from 2010, named the Ecodesign Regulation (EC) No 1016/2010. A new Ecodesign Regulation was issued on the 1st of March 2021, during the writing of this study. These calculations can be performed to comply with the new labelling scheme as well, following the same principle.

Each energy label is assigned an *EEI*, Energy Efficiency Index. The energy efficiency index is a number for how much energy is required to power the dishwasher for a full year, compared to a standard amount of energy required by a dishwasher of the same size. It is calculated as:

$$EEI = \frac{AEc}{SAEc} \cdot 100 \tag{E.1}$$

where AEc represents the Annual Energy Consumption for that specific dishwasher, and SAEc represents the Standard Annual Energy Consumption. How the AEc for a specific dishwasher is calculated is described in the Ecodesign Regulation (EC) No 1016/2010 CITE.

The SAEc is calculated for different place setting capacities, *ps*, by either of the following two formulas as follows:

If ps $\geq$ 10 and the dishwasher has a width $>$ 50 cm:

$$SAEc = 7.0 \cdot ps + 378$$

If ps $\leq$ 9, or else if ps $>$ 9 and the dishwasher has a width $\leq$ 50 cm:

$$SAEc = 25.2 \cdot ps + 126$$

We have for this assessment considered two arbitrary dishwashers; one which we call "Small", with ps = 9 and one which we call "Large". with ps = 13. The large dishwasher is considered to have a width $>$ 50 cm. We can thus calculate their respective SAEc values.

$$SAEc_{small} = 25.2 \cdot 9 + 126 = 352.8 \text{ kWh / year}$$

$$SAEc_{large} = 7.0 \cdot 13 + 378 = 469 \text{ kWh / year}$$

In table E.1 below, we have listed the different *EEI*s of the different energy labels. The standard recognizes energy labels from D to A+++, but since dishwashers of energy label C and D have practically not been sold during the last 10 years [45] (almost an entire dishwasher life time), we consider these to be irrelevant and they are thus omitted.

Table E.1: Energy Efficiency Index *EEI* for different energy labels

A+++	EEI < 50
A++	50 ≤ EEI < 56
A+	56 ≤ EEI < 63
A	63 ≤ EEI < 71
B	71 ≤ EEI < 80

We have in this project assumed that a dishwasher of a certain energy label will have an as high EEI as is allowed, which has been observed to be common [45]. Using equation E.1, we can thus calculate the assumed AEc of an arbitrary dishwasher of a certain energy label and size *ps*.

Table E.2: Assumed annual energy use of an arbitrary, small dishwasher

A+++	176.4
A++	194.04
A+	218.74
A	246.96
B	278.71

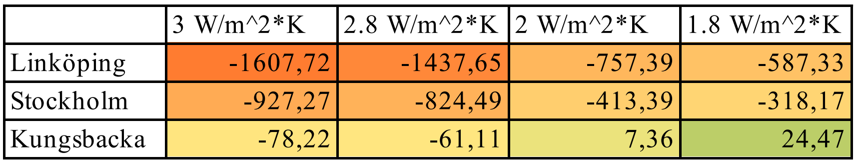
Table E.3: Assumed annual energy use of an arbitrary, large dishwasher

A+++	234.5
A++	257.95
A+	290.78
A	328.3
B	370.51

F

Sensitivity analysis - Window

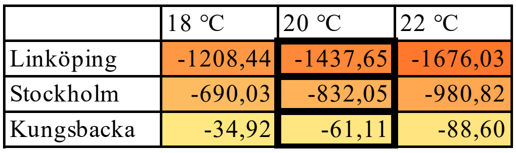
F.1 Sensitivity of U-value



	3 W/m^2*K	2.8 W/m^2*K	2 W/m^2*K	1.8 W/m^2*K
Linköping	-1607,72	-1437,65	-757,39	-587,33
Stockholm	-927,27	-824,49	-413,39	-318,17
Kungsbacka	-78,22	-61,11	7,36	24,47

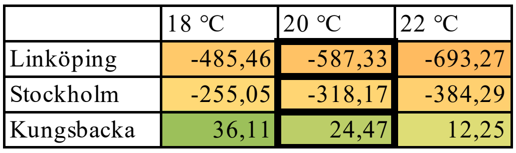
Figure F.1: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed U-value for the reused window installed in scenario 2.

F.2 Sensitivity of indoor temperature



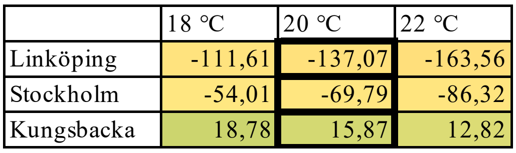
	18 °C	20 °C	22 °C
Linköping	-1208,44	-1437,65	-1676,03
Stockholm	-690,03	-832,05	-980,82
Kungsbacka	-34,92	-61,11	-88,60

Figure F.2: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed indoor temperature. In this figure the the U-value for the reused window installed in scenario 2 equal to 2.8 W/m^2·k.



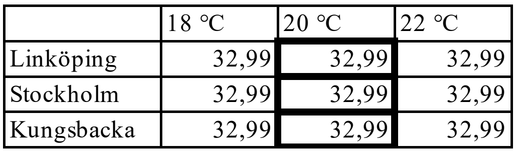
	18 °C	20 °C	22 °C
Linköping	-485,46	-587,33	-693,27
Stockholm	-255,05	-318,17	-384,29
Kungsbacka	36,11	24,47	12,25

Figure F.3: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed indoor temperature. In this figure the the U-value for the reused window installed in scenario 2 equal to 1.8 W/m^2·k.



	18 °C	20 °C	22 °C
Linköping	-111,61	-137,07	-163,56
Stockholm	-54,01	-69,79	-86,32
Kungsbacka	18,78	15,87	12,82

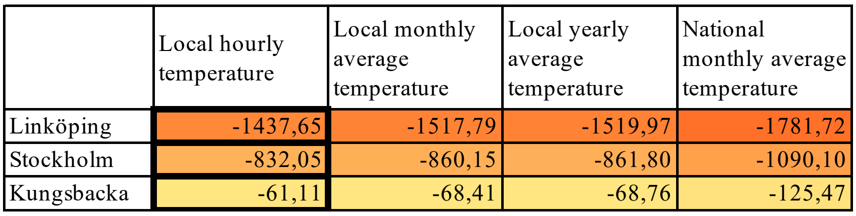
Figure F.4: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed indoor temperature. In this figure the the U-value for the reconditioned and reused window installed in scenario 3 equal to 1.2 W/m^2·k.



	18 °C	20 °C	22 °C
Linköping	32,99	32,99	32,99
Stockholm	32,99	32,99	32,99
Kungsbacka	32,99	32,99	32,99

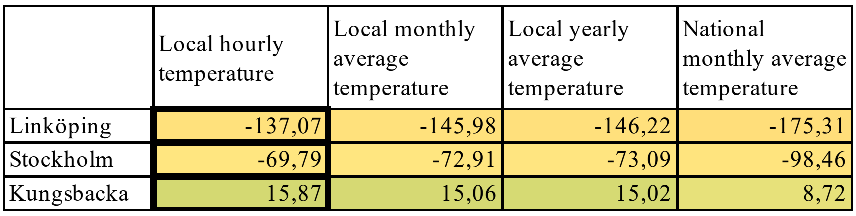
Figure F.5: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed indoor temperature. In this figure the the U-value for the reconditioned and reused window installed in scenario 3 equal to 1.0 W/m^2·k.

F.3 Sensitivity of outdoor temperature



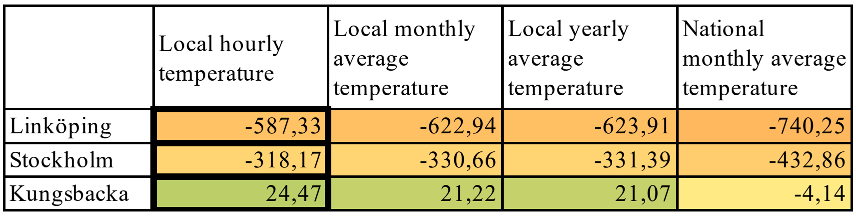
	Local hourly temperature	Local monthly average temperature	Local yearly average temperature	National monthly average temperature
Linköping	-1437,65	-1517,79	-1519,97	-1781,72
Stockholm	-832,05	-860,15	-861,80	-1090,10
Kungsbacka	-61,11	-68,41	-68,76	-125,47

Figure F.6: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed outdoor temperature. In this figure the the U-value for the reused window installed in scenario 2 equal to 2.8 W/m^2·k.



	Local hourly temperature	Local monthly average temperature	Local yearly average temperature	National monthly average temperature
Linköping	-137,07	-145,98	-146,22	-175,31
Stockholm	-69,79	-72,91	-73,09	-98,46
Kungsbacka	15,87	15,06	15,02	8,72

Figure F.7: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed outdoor temperature. In this figure the the U-value for the reused window installed in scenario 2 equal to 1.8 W/m^2·k.



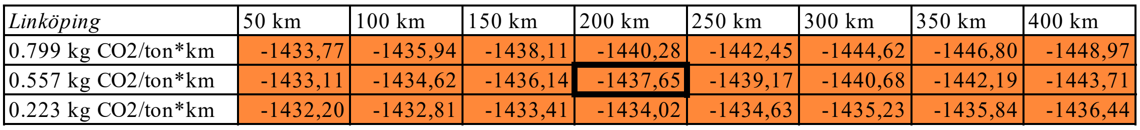
	Local hourly temperature	Local monthly average temperature	Local yearly average temperature	National monthly average temperature
Linköping	-587,33	-622,94	-623,91	-740,25
Stockholm	-318,17	-330,66	-331,39	-432,86
Kungsbacka	24,47	21,22	21,07	-4,14

Figure F.8: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed outdoor temperature. In this figure the the U-value for the reconditioned and reused window installed in scenario 3 equal to 1.2 W/m^2·k.

	Local hourly temperature	Local monthly average temperature	Local yearly average temperature	National monthly average temperature
Linköping	32,99	32,99	32,99	32,99
Stockholm	32,99	32,99	32,99	32,99
Kungsbacka	32,99	32,99	32,99	32,99

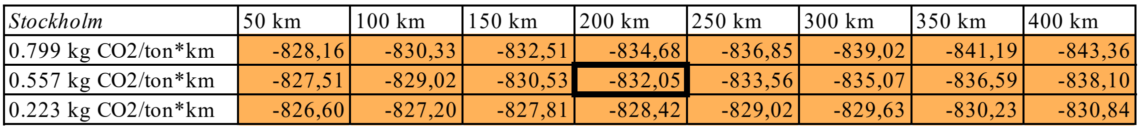
Figure F.9: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed outdoor temperature. In this figure the the U-value for the reconditioned and reused window installed in scenario 3 equal to 1.0 W/m^2·k.

F.4 Sensitivity of transport for reuse



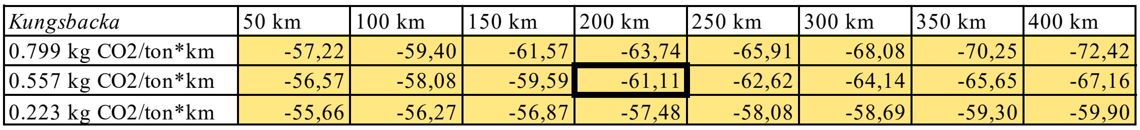
Linköping	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-1433,77	-1435,94	-1438,11	-1440,28	-1442,45	-1444,62	-1446,80	-1448,97
0.557 kg CO2/ton*km	-1433,11	-1434,62	-1436,14	-1437,65	-1439,17	-1440,68	-1442,19	-1443,71
0.223 kg CO2/ton*km	-1432,20	-1432,81	-1433,41	-1434,02	-1434,63	-1435,23	-1435,84	-1436,44

Figure F.10: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Linköping and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



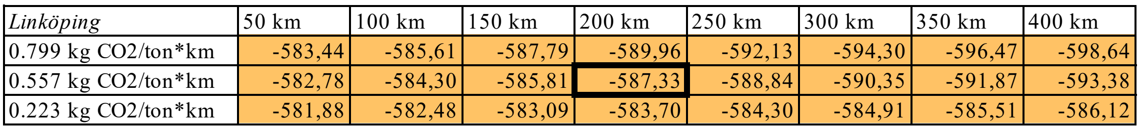
Stockholm	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-828,16	-830,33	-832,51	-834,68	-836,85	-839,02	-841,19	-843,36
0.557 kg CO2/ton*km	-827,51	-829,02	-830,53	-832,05	-833,56	-835,07	-836,59	-838,10
0.223 kg CO2/ton*km	-826,60	-827,20	-827,81	-828,42	-829,02	-829,63	-830,23	-830,84

Figure F.11: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Stockholm and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



Kungsbacka	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-57,22	-59,40	-61,57	-63,74	-65,91	-68,08	-70,25	-72,42
0.557 kg CO2/ton*km	-56,57	-58,08	-59,59	-61,11	-62,62	-64,14	-65,65	-67,16
0.223 kg CO2/ton*km	-55,66	-56,27	-56,87	-57,48	-58,08	-58,69	-59,30	-59,90

Figure F.12: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Kungsbacka and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



Linköping	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-583,44	-585,61	-587,79	-589,96	-592,13	-594,30	-596,47	-598,64
0.557 kg CO2/ton*km	-582,78	-584,30	-585,81	-587,33	-588,84	-590,35	-591,87	-593,38
0.223 kg CO2/ton*km	-581,88	-582,48	-583,09	-583,70	-584,30	-584,91	-585,51	-586,12

Figure F.13: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Linköping and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.

Stockholm	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-314,28	-316,46	-318,63	-320,80	-322,97	-325,14	-327,31	-329,48
0.557 kg CO2/ton*km	-313,63	-315,14	-316,65	-318,17	-319,68	-321,20	-322,71	-324,22
0.223 kg CO2/ton*km	-312,72	-313,33	-313,93	-314,54	-315,14	-315,75	-316,36	-316,96

Figure F.14: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Stockholm and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.

Kungsbacka	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	28,35	26,18	24,01	21,84	19,67	17,50	15,33	13,16
0.557 kg CO2/ton*km	29,01	27,50	25,98	24,47	22,96	21,44	19,93	18,42
0.223 kg CO2/ton*km	29,92	29,31	28,71	28,10	27,50	26,89	26,28	25,68

Figure F.15: Results presenting the difference in climate impact between scenario 1 and 2 depending on carbon intensity from transport and distance. In this figure the location is Kungsbacka and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.

Linköping	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-127,14	-129,31	-131,48	-133,65	-135,82	-137,99	-140,16	-142,34
0.557 kg CO2/ton*km	-126,48	-127,99	-129,51	-131,02	-132,53	-134,05	-135,56	-137,07
0.223 kg CO2/ton*km	-125,57	-126,18	-126,78	-127,39	-128,00	-128,60	-129,21	-129,81

Figure F.16: Results presenting the difference in climate impact between scenario 1 and 3 depending on carbon intensity from transport and distance. In this figure the location is Linköping and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.

Stockholm	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	-59,85	-62,02	-64,19	-66,36	-68,53	-70,70	-72,88	-75,05
0.557 kg CO2/ton*km	-59,19	-60,70	-62,22	-63,73	-65,24	-66,76	-68,27	-69,79
0.223 kg CO2/ton*km	-58,28	-58,89	-59,49	-60,10	-60,71	-61,31	-61,92	-62,52

Figure F.17: Results presenting the difference in climate impact between scenario 1 and 3 depending on carbon intensity from transport and distance. In this figure the location is Stockholm and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.

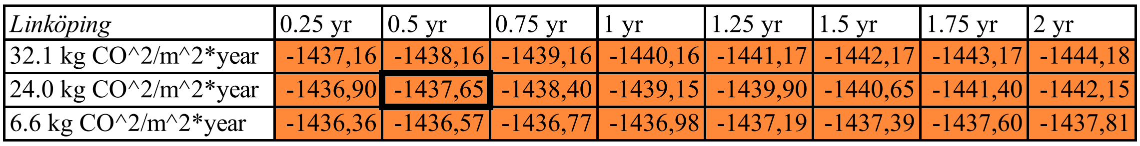
Kungsbacka	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	25,81	23,64	21,47	19,30	17,13	14,96	12,78	10,61
0.557 kg CO2/ton*km	26,47	24,96	23,44	21,93	20,42	18,90	17,39	15,87
0.223 kg CO2/ton*km	27,38	26,77	26,17	25,56	24,95	24,35	23,74	23,14

Figure F.18: Results presenting the difference in climate impact between scenario 1 and 3 depending on carbon intensity from transport and distance. In this figure the location is Kungsbacka and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.

	50 km	100 km	150 km	200 km	250 km	300 km	350 km	400 km
0.799 kg CO2/ton*km	42,93	40,76	38,59	36,41	34,24	32,07	29,90	27,73
0.557 kg CO2/ton*km	43,59	42,07	40,56	39,04	37,53	36,02	34,50	32,99
0.223 kg CO2/ton*km	44,49	43,89	43,28	42,68	42,07	41,46	40,86	40,25

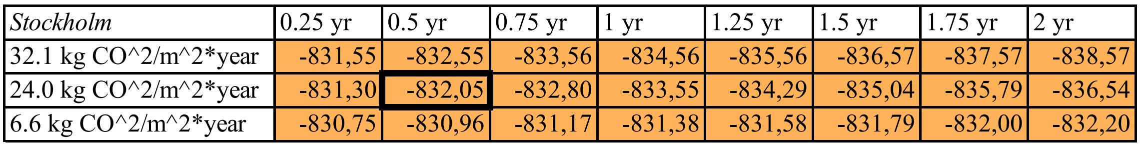
Figure F.19: Results presenting the difference in climate impact between scenario 1 and 3 depending on carbon intensity from transport and distance. In this figure the location is arbitrary and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.0 W/m^2·k.

F.5 Sensitivity of storage during reuse



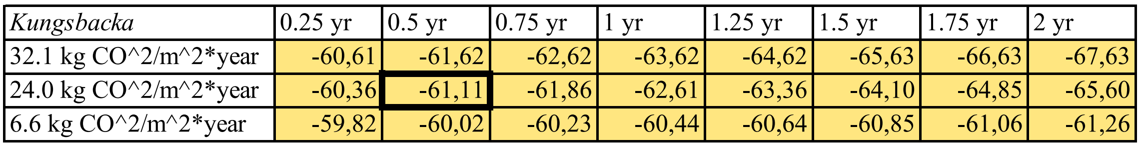
Linköping	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-1437,16	-1438,16	-1439,16	-1440,16	-1441,17	-1442,17	-1443,17	-1444,18
24.0 kg CO^2/m^2*year	-1436,90	-1437,65	-1438,40	-1439,15	-1439,90	-1440,65	-1441,40	-1442,15
6.6 kg CO^2/m^2*year	-1436,36	-1436,57	-1436,77	-1436,98	-1437,19	-1437,39	-1437,60	-1437,81

Figure F.20: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Linköping and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



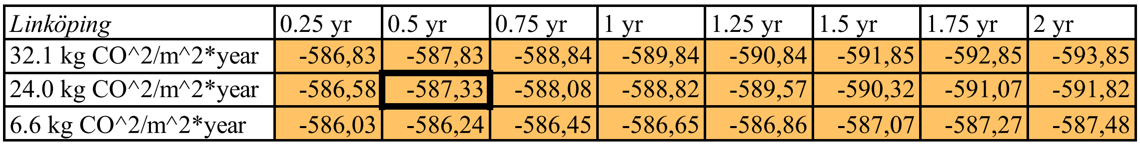
Stockholm	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-831,55	-832,55	-833,56	-834,56	-835,56	-836,57	-837,57	-838,57
24.0 kg CO^2/m^2*year	-831,30	-832,05	-832,80	-833,55	-834,29	-835,04	-835,79	-836,54
6.6 kg CO^2/m^2*year	-830,75	-830,96	-831,17	-831,38	-831,58	-831,79	-832,00	-832,20

Figure F.21: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Stockholm and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



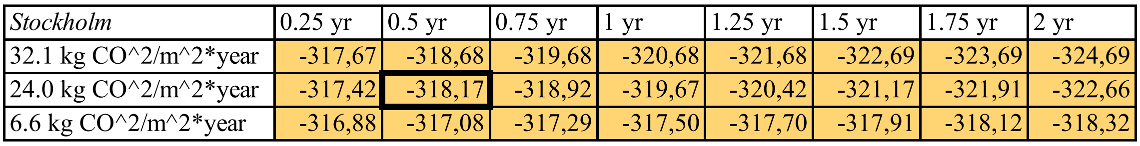
Kungsbacka	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-60,61	-61,62	-62,62	-63,62	-64,62	-65,63	-66,63	-67,63
24.0 kg CO^2/m^2*year	-60,36	-61,11	-61,86	-62,61	-63,36	-64,10	-64,85	-65,60
6.6 kg CO^2/m^2*year	-59,82	-60,02	-60,23	-60,44	-60,64	-60,85	-61,06	-61,26

Figure F.22: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Kungsbacka and the U-value for the reused window installed in scenario 2 is equal to 2.8 W/m^2·k.



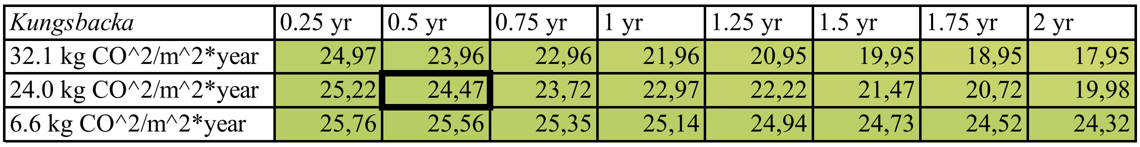
Linköping	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-586,83	-587,83	-588,84	-589,84	-590,84	-591,85	-592,85	-593,85
24.0 kg CO^2/m^2*year	-586,58	-587,33	-588,08	-588,82	-589,57	-590,32	-591,07	-591,82
6.6 kg CO^2/m^2*year	-586,03	-586,24	-586,45	-586,65	-586,86	-587,07	-587,27	-587,48

Figure F.23: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Linköping and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.



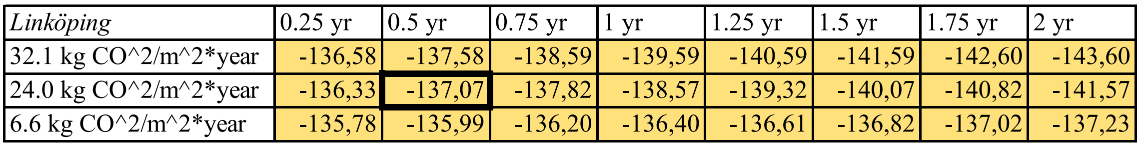
Stockholm	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-317,67	-318,68	-319,68	-320,68	-321,68	-322,69	-323,69	-324,69
24.0 kg CO^2/m^2*year	-317,42	-318,17	-318,92	-319,67	-320,42	-321,17	-321,91	-322,66
6.6 kg CO^2/m^2*year	-316,88	-317,08	-317,29	-317,50	-317,70	-317,91	-318,12	-318,32

Figure F.24: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Stockholm and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.



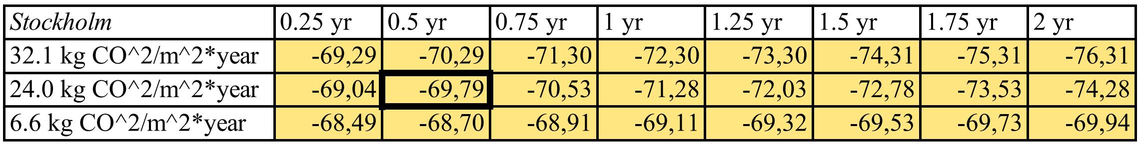
Kungsbacka	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	24,97	23,96	22,96	21,96	20,95	19,95	18,95	17,95
24.0 kg CO^2/m^2*year	25,22	24,47	23,72	22,97	22,22	21,47	20,72	19,98
6.6 kg CO^2/m^2*year	25,76	25,56	25,35	25,14	24,94	24,73	24,52	24,32

Figure F.25: Results presenting the difference in climate impact between scenario 1 and 2 depending on assumed carbon intensity from storage and storage time. In this figure the location is Kungsbacka and the U-value for the reused window installed in scenario 2 is equal to 1.8 W/m^2·k.



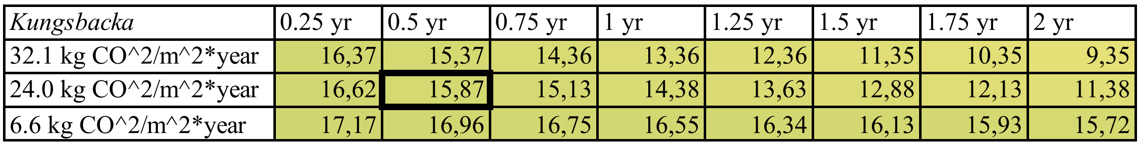
Linköping	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-136,58	-137,58	-138,59	-139,59	-140,59	-141,59	-142,60	-143,60
24.0 kg CO^2/m^2*year	-136,33	-137,07	-137,82	-138,57	-139,32	-140,07	-140,82	-141,57
6.6 kg CO^2/m^2*year	-135,78	-135,99	-136,20	-136,40	-136,61	-136,82	-137,02	-137,23

Figure F.26: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from storage and storage time. In this figure the location is Linköping and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.



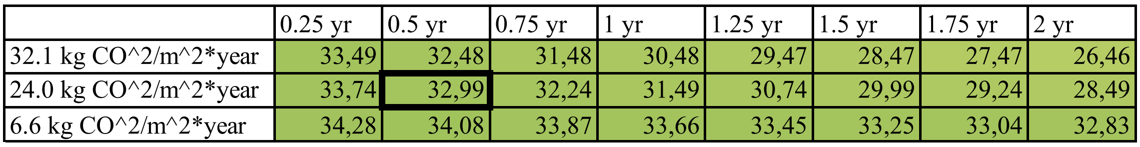
Stockholm	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	-69,29	-70,29	-71,30	-72,30	-73,30	-74,31	-75,31	-76,31
24.0 kg CO^2/m^2*year	-69,04	-69,79	-70,53	-71,28	-72,03	-72,78	-73,53	-74,28
6.6 kg CO^2/m^2*year	-68,49	-68,70	-68,91	-69,11	-69,32	-69,53	-69,73	-69,94

Figure F.27: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from storage and storage time. In this figure the location is Stockholm and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.



Kungsbacka	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	16,37	15,37	14,36	13,36	12,36	11,35	10,35	9,35
24.0 kg CO^2/m^2*year	16,62	15,87	15,13	14,38	13,63	12,88	12,13	11,38
6.6 kg CO^2/m^2*year	17,17	16,96	16,75	16,55	16,34	16,13	15,93	15,72

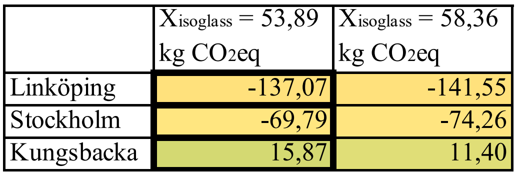
Figure F.28: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from storage and storage time. In this figure the location is Kungsbacka and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.



	0.25 yr	0.5 yr	0.75 yr	1 yr	1.25 yr	1.5 yr	1.75 yr	2 yr
32.1 kg CO^2/m^2*year	33,49	32,48	31,48	30,48	29,47	28,47	27,47	26,46
24.0 kg CO^2/m^2*year	33,74	32,99	32,24	31,49	30,74	29,99	29,24	28,49
6.6 kg CO^2/m^2*year	34,28	34,08	33,87	33,66	33,45	33,25	33,04	32,83

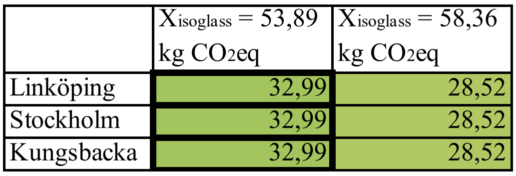
Figure F.29: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from storage and storage time. In this figure the location is arbitrary and the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.0 W/m^2·k.

F.6 Sensitivity of reconditioning



	$X_{isoglass}$ = 53,89 kg CO_2eq	$X_{isoglass}$ = 58,36 kg CO_2eq
Linköping	-137,07	-141,55
Stockholm	-69,79	-74,26
Kungsbacka	15,87	11,40

Figure F.30: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from reconditioning. In this figure the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.2 W/m^2·k.



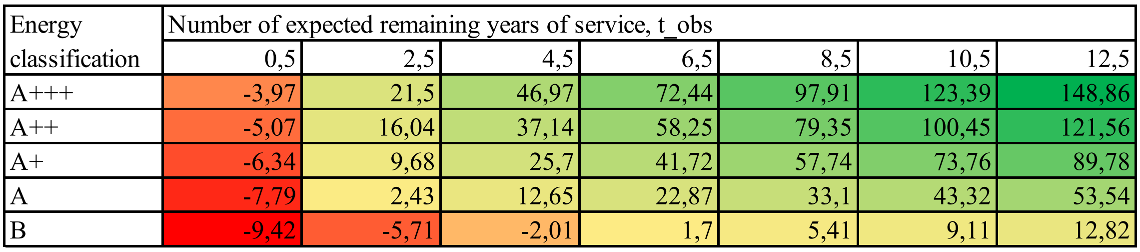
	$X_{isoglass}$ = 53,89 kg CO_2eq	$X_{isoglass}$ = 58,36 kg CO_2eq
Linköping	32,99	28,52
Stockholm	32,99	28,52
Kungsbacka	32,99	28,52

Figure F.31: Results presenting the difference in climate impact between scenario 1 and 3 depending on assumed carbon intensity from reconditioning. In this figure the U-value for the reconditioned and reused window installed in scenario 3 is equal to 1.0 W/m^2·k.

G

Sensitivity analysis - Dishwasher

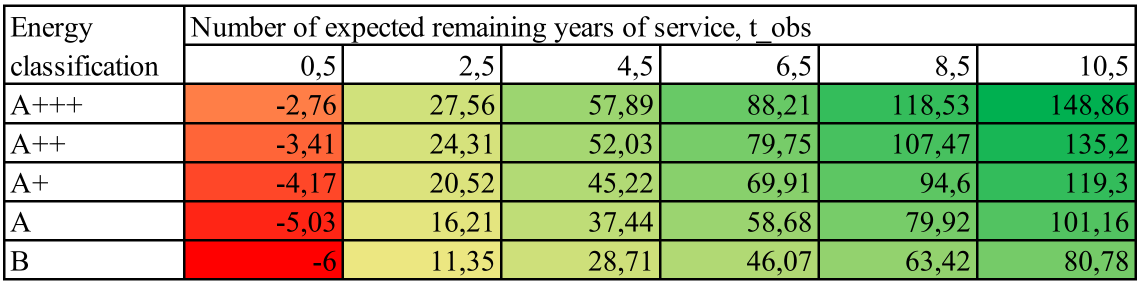
G.1 Sensitivity of use frequency



Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-3,97	21,5	46,97	72,44	97,91	123,39	148,86
A++	-5,07	16,04	37,14	58,25	79,35	100,45	121,56
A+	-6,34	9,68	25,7	41,72	57,74	73,76	89,78
A	-7,79	2,43	12,65	22,87	33,1	43,32	53,54
B	-9,42	-5,71	-2,01	1,7	5,41	9,11	12,82

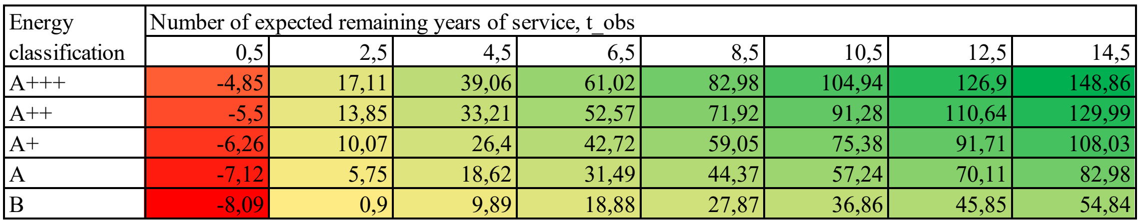
Figure G.1: The new result when assuming 470 uses per year

G.2 Sensitivity of expected technical service time



Energy classification	Number of expected remaining years of service, t_obs					
	0,5	2,5	4,5	6,5	8,5	10,5
A+++	-2,76	27,56	57,89	88,21	118,53	148,86
A++	-3,41	24,31	52,03	79,75	107,47	135,2
A+	-4,17	20,52	45,22	69,91	94,6	119,3
A	-5,03	16,21	37,44	58,68	79,92	101,16
B	-6	11,35	28,71	46,07	63,42	80,78

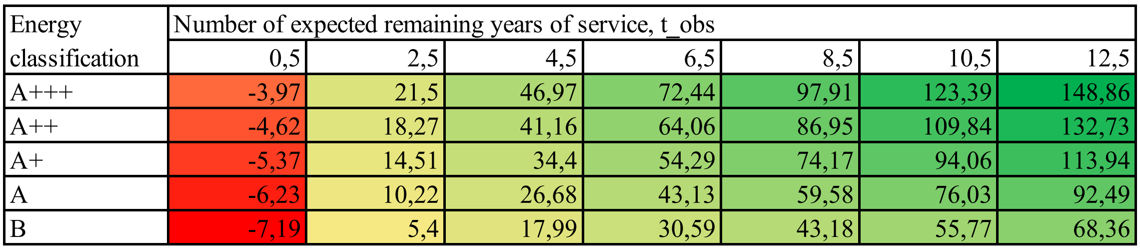
Figure G.2: The new result when assuming an expected technical service life of 10.5 years.



Energy classification	Number of expected remaining years of service, t_obs							
	0,5	2,5	4,5	6,5	8,5	10,5	12,5	14,5
A+++	-4,85	17,11	39,06	61,02	82,98	104,94	126,9	148,86
A++	-5,5	13,85	33,21	52,57	71,92	91,28	110,64	129,99
A+	-6,26	10,07	26,4	42,72	59,05	75,38	91,71	108,03
A	-7,12	5,75	18,62	31,49	44,37	57,24	70,11	82,98
B	-8,09	0,9	9,89	18,88	27,87	36,86	45,85	54,84

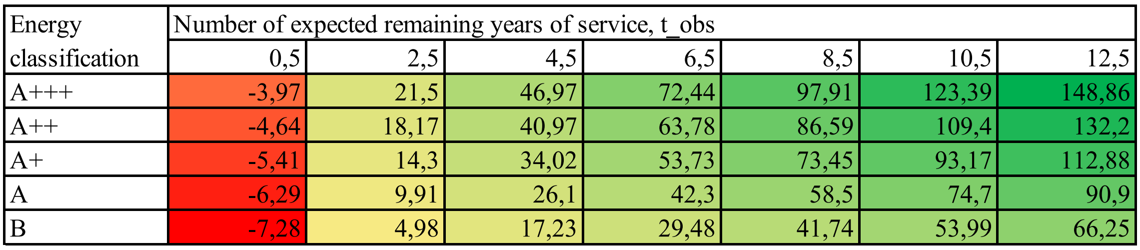
Figure G.3: The new result when assuming an expected technical service life of 14.5 years.

G.3 Sensitivity of energy efficiency at local water treatment facility



Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-3,97	21,5	46,97	72,44	97,91	123,39	148,86
A++	-4,62	18,27	41,16	64,06	86,95	109,84	132,73
A+	-5,37	14,51	34,4	54,29	74,17	94,06	113,94
A	-6,23	10,22	26,68	43,13	59,58	76,03	92,49
B	-7,19	5,4	17,99	30,59	43,18	55,77	68,36

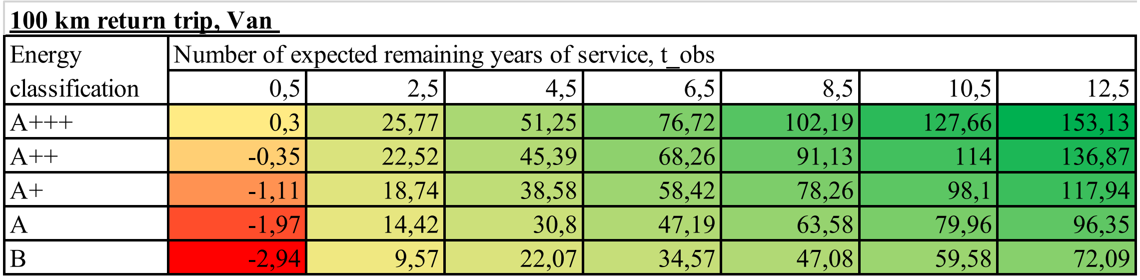
Figure G.4: The new result higher energy efficiency water treatment.



Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-3,97	21,5	46,97	72,44	97,91	123,39	148,86
A++	-4,64	18,17	40,97	63,78	86,59	109,4	132,2
A+	-5,41	14,3	34,02	53,73	73,45	93,17	112,88
A	-6,29	9,91	26,1	42,3	58,5	74,7	90,9
B	-7,28	4,98	17,23	29,48	41,74	53,99	66,25

Figure G.5: The new result lower energy efficiency water treatment.

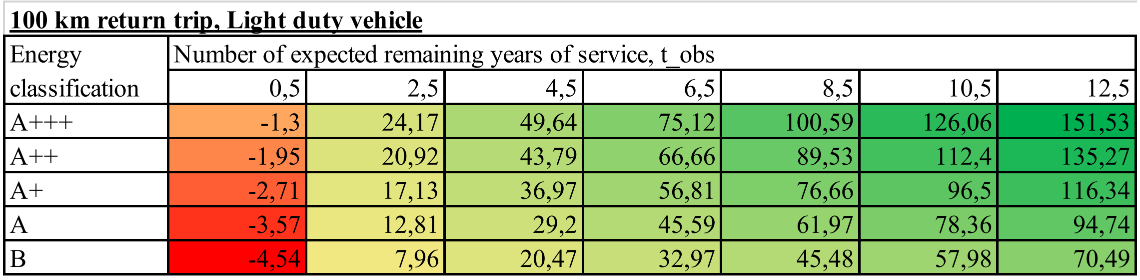
G.4 Sensitivity of transport for reuse



100 km return trip, Van

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	0,3	25,77	51,25	76,72	102,19	127,66	153,13
A++	-0,35	22,52	45,39	68,26	91,13	114	136,87
A+	-1,11	18,74	38,58	58,42	78,26	98,1	117,94
A	-1,97	14,42	30,8	47,19	63,58	79,96	96,35
B	-2,94	9,57	22,07	34,57	47,08	59,58	72,09

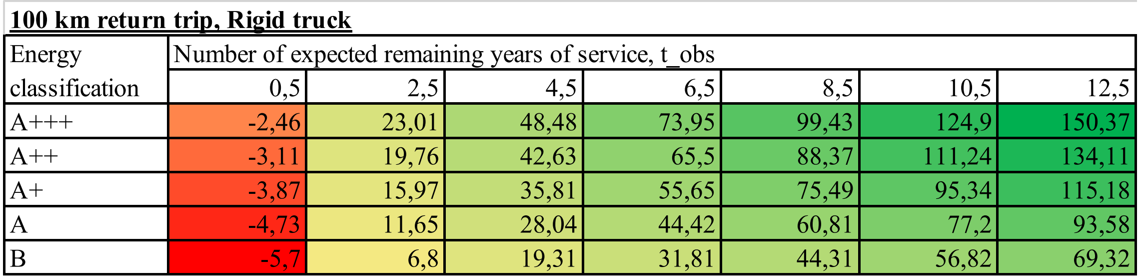
Figure G.6: The new result when assuming transportation for 100 km in a Van.



100 km return trip, Light duty vehicle

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-1,3	24,17	49,64	75,12	100,59	126,06	151,53
A++	-1,95	20,92	43,79	66,66	89,53	112,4	135,27
A+	-2,71	17,13	36,97	56,81	76,66	96,5	116,34
A	-3,57	12,81	29,2	45,59	61,97	78,36	94,74
B	-4,54	7,96	20,47	32,97	45,48	57,98	70,49

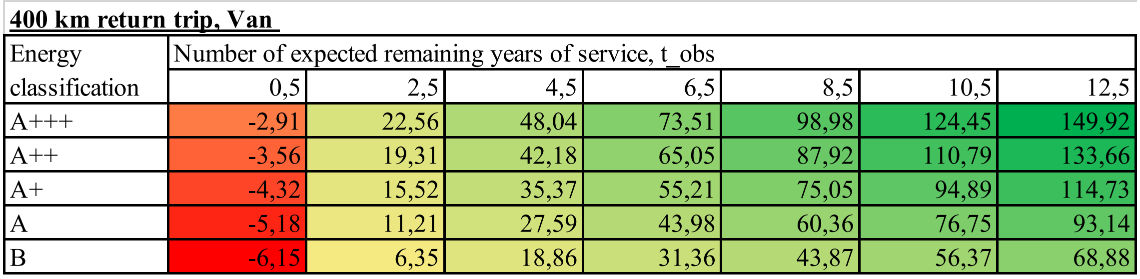
Figure G.7: The new result when assuming transportation for 100 km in a Light Duty Vehicle.



100 km return trip, Rigid truck

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-2,46	23,01	48,48	73,95	99,43	124,9	150,37
A++	-3,11	19,76	42,63	65,5	88,37	111,24	134,11
A+	-3,87	15,97	35,81	55,65	75,49	95,34	115,18
A	-4,73	11,65	28,04	44,42	60,81	77,2	93,58
B	-5,7	6,8	19,31	31,81	44,31	56,82	69,32

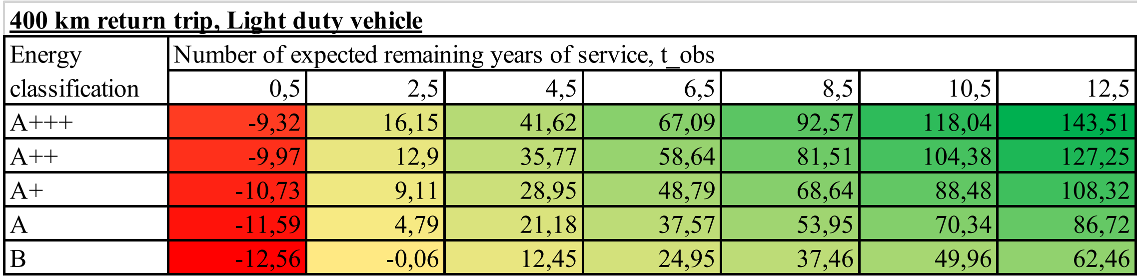
Figure G.8: The new result when assuming transportation for 100 km in a Rigid truck.



400 km return trip, Van

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-2,91	22,56	48,04	73,51	98,98	124,45	149,92
A++	-3,56	19,31	42,18	65,05	87,92	110,79	133,66
A+	-4,32	15,52	35,37	55,21	75,05	94,89	114,73
A	-5,18	11,21	27,59	43,98	60,36	76,75	93,14
B	-6,15	6,35	18,86	31,36	43,87	56,37	68,88

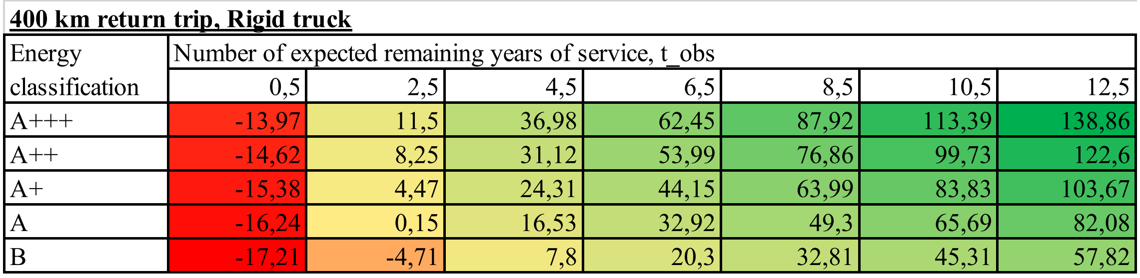
[Sensitivity of R1 - Transport (4)]The new result when assuming transportation for 400 km in a Van.



400 km return trip, Light duty vehicle

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-9,32	16,15	41,62	67,09	92,57	118,04	143,51
A++	-9,97	12,9	35,77	58,64	81,51	104,38	127,25
A+	-10,73	9,11	28,95	48,79	68,64	88,48	108,32
A	-11,59	4,79	21,18	37,57	53,95	70,34	86,72
B	-12,56	-0,06	12,45	24,95	37,46	49,96	62,46

Figure G.9: The new result when assuming transportation for 400 km in a Light Duty Vehicle.

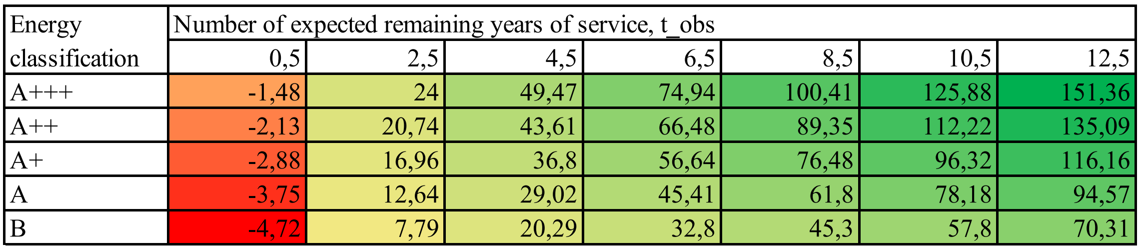


400 km return trip, Rigid truck

Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-13,97	11,5	36,98	62,45	87,92	113,39	138,86
A++	-14,62	8,25	31,12	53,99	76,86	99,73	122,6
A+	-15,38	4,47	24,31	44,15	63,99	83,83	103,67
A	-16,24	0,15	16,53	32,92	49,3	65,69	82,08
B	-17,21	-4,71	7,8	20,3	32,81	45,31	57,82

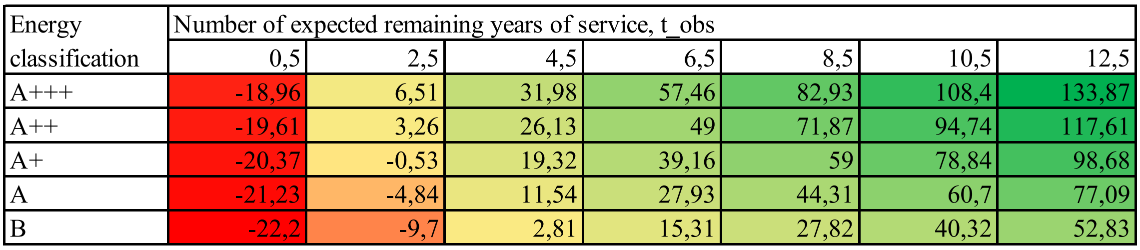
Figure G.10: The new result when assuming transportation for 400 km in a Rigid truck.

G.5 Sensitivity of storage during reuse



Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-1,48	24	49,47	74,94	100,41	125,88	151,36
A++	-2,13	20,74	43,61	66,48	89,35	112,22	135,09
A+	-2,88	16,96	36,8	56,64	76,48	96,32	116,16
A	-3,75	12,64	29,02	45,41	61,8	78,18	94,57
B	-4,72	7,79	20,29	32,8	45,3	57,8	70,31

Figure G.11: New results when assuming 3 months storage



Energy classification	Number of expected remaining years of service, t_obs						
	0,5	2,5	4,5	6,5	8,5	10,5	12,5
A+++	-18,96	6,51	31,98	57,46	82,93	108,4	133,87
A++	-19,61	3,26	26,13	49	71,87	94,74	117,61
A+	-20,37	-0,53	19,32	39,16	59	78,84	98,68
A	-21,23	-4,84	11,54	27,93	44,31	60,7	77,09
B	-22,2	-9,7	2,81	15,31	27,82	40,32	52,83

Figure G.12: New results when assuming 24 months storage

H

Calculations - Guideline

Emissions should been calculated for each module in the products life cycle separately. The variables representing the total emissions from each module are presented in table H.1 connected.

Table H.1: Variables for emissions from different life cycle stages

	Module A	Module B	Module R	Module C
Linear option	X_A	$X_{B,new}$	-	X_C
Circular option	-	$X_{B,old}$	X_R	-

The following sections will describe how to calculate each process within the use- and reuse phase (module B and R). For products which all processes are not relevant, the irrelevant processes may simply be cut out of the calculations.

H.1 Module B

This process may include process B6 Operational Energy and B7 Operational Water. Only include the process relevant to the studied product. How to calculate process B6 may also vary depending on how the studied product consume/give rise to consumption of energy. To different guidelines are therefore presented.

H.1.1 B6 Operational Energy - Building envelope

$$X_{B6:new} = A \cdot U_{new} \cdot (T_{in} - T_{out}) \cdot C_{heat} \cdot t \tag{H.1}$$

$$X_{B6:old} = A \cdot U_{old} \cdot (T_{in} - T_{out}) \cdot C_{heat} \cdot t \tag{H.2}$$

Table H.2: All parameters used in calculations for B6 Operational Energy - Building envelope

Parameter	**Variable**
Carbon Intensity for district heating	C_{heat} [kg CO_2-eq/kWh]
Studied time frame	t [years]
Product area	A [m^2]
U-value of the old product	U_{old} [$W/m^2 \cdot K$]
U-value of the new product	U_{new} [$W/m^2 \cdot K$]
Indoor temperature	T_{in} [°C]
Outdoor temperature	T_{out} [°C]

H.1.2 B6 Operational Energy - Appliances

$$X_{B6:new} = E_{new} \cdot C_{elec} \cdot t \tag{H.3}$$

$$X_{B6:old} = E_{old} \cdot C_{elec} \cdot t \tag{H.4}$$

$$\tag{H.5}$$

Table H.3: All parameters used in calculations for B6 Operational Energy, for a dishwasher or similar appliance. The studied timeframe is the expected remaining service time of the older appliance. The annual energy use is calculated using the energy label and size of the appliance (see appendix E).

Parameter	**Variable**
Carbon intensity for electricity consumption	C_{elec} [kg CO_2-eq/kWh]
Studied time frame	t [years]
Annual energy use, older appliance	E_{old} [kWh]
Annual energy use, new appliance	E_{new} [kWh]

H.1.3 B7 Operational Water

$$X_{B7:new} = C_{water} \cdot V_{new} \cdot t \tag{H.6}$$

$$X_{B7:old} = C_{water} \cdot V_{old} \cdot t \tag{H.7}$$

$$C_{water} = C_{elec} \cdot E_{water-elec} \cdot W \tag{H.8}$$

Table H.4: All parameters used in calculations for B7 Operational Water

Parameter	**Variable**
Carbon intensity for water pumping and purification	C_{water} [kg CO^2/m^3]
Water consumption	V [m^3]
Observed time span for the functional unit of the study	t [years]
Carbon intensity from electricity consumption	C_{elec} [kg CO$_2$-eq/kWh]
Energy consumption from water pumping and purification	$E_{water-elec}$ [kWh/m^3]
Wash cycles per year	W [st]

H.2 Module R

This module may include process R1 Transport to storage, R2 Storage, R3 Transport to reconditioning and R4 Reconditioning. Only include the process relevant to the studied product.

H.2.1 R1 & R3 Transport

$$X_{R1}, X_{R3} = C_{transp} \cdot d \cdot m \tag{H.9}$$

Table H.5: All parameters used in calculations for R1 & R3 Transport

Parameter	**Variable**
Distance	d [km]
Carbon intensity from transport	C_{transp} [kg CO$_2$-eq/ton·km]
Weight	m [kg]

H.2.2 R2 Storage

$$X_{R2} = \frac{C_{elec} \cdot Q_{elec/year} + C_{heat} \cdot Q_{heat/year}}{n_s \cdot F_{fill}} \cdot A_{floor} \cdot t_{storage} \tag{H.10}$$

Table H.6: All parameters used in calculations for R2 Storage

Parameter	**Variable**
Number of shelf levels	n_s [st]
Fill rate	F_{fill} [-]
Storage time	$\mathrm{t}_{storage}$ [years]
Covered floor area per product	A_{floor} [m^2]
Storage yearly electricity consumption	$\mathrm{Q}_{elec/year}$ [kWh/m^2]
Storage yearly heating consumption	$\mathrm{Q}_{heat/year}$ [kWh/m^2]
Carbon intensity from electricity consumption	C_{elec} [kg CO^2/kWh]
Carbon intensity from district heating	C_{heat} [kg CO^2/kWh]

H.2.3 R4 Reconditioning

$$X_{R4} = m_p \cdot X_A \tag{H.11}$$

Table H.7: All parameters used in calculations for R4 Reconditioning

Parameter	**Variable**
Mass percentage of the exchanged part of the product in relation to the total product mass	m_p [-]
Climate impact from module A	X_A [kg CO$_2$-eq]

H.3 Final calculation of difference in climate impact

The final calculations of the difference in climate impact between the linear and the circular scenario are calculated by subtracting the total climate impact from the studied processes in the circular scenario from the total climate impact from the studied processes in the linear scenario. For products with relatively long technical life times (such as products in the building envelope) $t_{service}$ is equal to t.

$$X_{new} = \frac{t}{t_{service}} \cdot (X_A + X_C) + X_{B:new} \tag{H.12}$$

$$X_{old} = X_R + X_{B:old} \tag{H.13}$$

$$\Delta X = X_{new} - X_{old} \tag{H.14}$$

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