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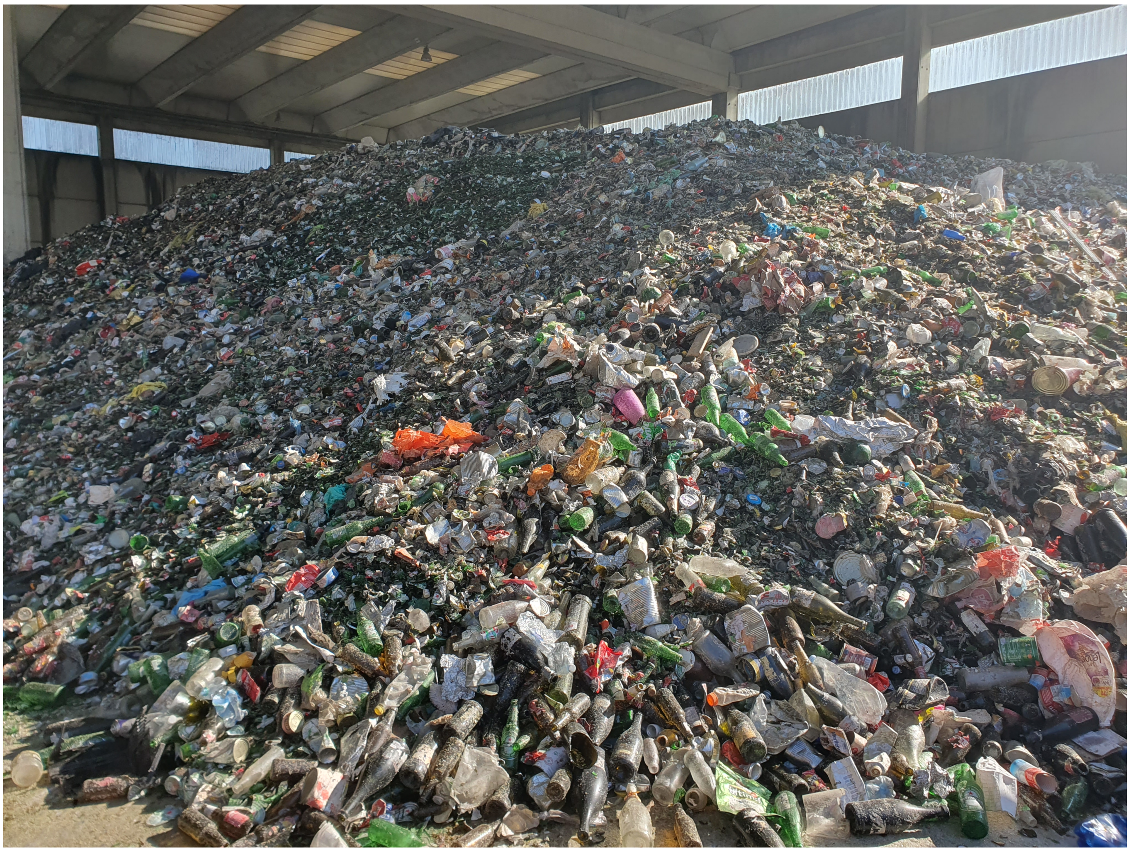

Quality Degradation from Recycling

Quality Degradation and Substitutability Between Glass Cullet and Virgin Raw Material in LCA

Master's thesis in Industrial Ecology

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Cover: The input stream of a glass sorting plant.

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Abstract

The focus in society to become more circular has increased lately and therefore also the focus on recycling. Recycling is a key factor to keep the material inside the loop, but an important aspect of the applicability of the secondary material is its quality and its possibility to replace virgin raw material. The benefit of recycling is therefore depending on the quality of the output product. Life cycle assessment (LCA) is often used as a tool to evaluate the benefits of recycling, however, the quality of the output product is seldom considered and there is no common and clear way how to evaluate the quality loss from recycling. A major problem lies in how to quantify to what degree the materials are functionally equal and by that substitutable, and in the quantification, it must be kept in mind that the secondary material might have gone through a quality degradation that would impact the substitutability. Most LCA studies do not consider this aspect and instead assume that the functionality of the secondary material is fully equal to the replaced material and can fully replace the material with a one-to-one (1:1) substitution rate.

A material that is commonly recycled and used as a secondary material is glass. Glass is often considered a fully circular material and few studies have focused on the quality degradation of glass, even though several aspects affect the quality of glass cullet as a secondary material. This thesis has therefore resulted in a proposal for evaluating quality degradation and for quantifying the substitutability of glass when recycled. The model takes its base in existing models for other materials and information regarding important factors and quality aspects of glass cullet. The model was then implemented in two case studies, one about the life cycle of a bottle and one regarding the treatment of waste glass. For each of the case studies, substitutability coefficients for the secondary material were calculated and the effect of using these instead of a 1:1 substitutability was compared. The results from the case studies were then used to evaluate the model and its functionality. The results showed that accounting for the quality degradation could have an important effect on the results of the study and the total impact of the system, especially when evaluating waste treatment systems. A proper way of quantifying the substitutability between the glass cullet and the replaced material is therefore important to evaluate the environmental impact of the studied system. Quantifying substitutability properly is difficult since the quality depends on many different aspects. The introduced model is therefore a simplification that is adapted for some quality aspects. It could be improved by evaluating the quality requirements for glass cullet further and by including more quality aspects and considering their relative importance.

Keywords: Substitutability, Secondary material, Quality Degradation, Recycling, Container Glass, Glass Cullet, Life cycle assessment, LCA.

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Emma Olsson, Gothenburg, April 2023

List of Acronyms

LCA	Life Cycle Assessment
EU	European Union
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
TP	Technical Property
SecM	Secondary Material
SubM	Substituted Material
TSC	Technical Substitutability Coefficient
TS	Technical Substitutability
CSP	Ceramics, Stones and Porcelain
Fe-	Ferrous
MS	Market Share
S	Substitutability
GWP	Global Warming Potential

List of Symbols

γ	Substitution Potential
U_{rec}	Physical Resource Potential of Recovered Material
η_{rec}	Resource Recovery Efficiency of Recovered Material
$\alpha_{rec,disp}$	Substitutability Between Recovered and Displaced Material
π_{disp}	Market Response of the Displaced Material
ϕ_{rec}	Functionality Recovered Material
ϕ_{disp}	Functionality Displaced Material
TP	Main Technical Property
$TP(SecM)$	Technical Property of the Secondary Material
$TP(SubM)$	Technical Property of the Substituted Material
TSC	Technical Substitutability Coefficient
RQ^{mech}	Mechanical Quality Factor
RQ^{proc}	Processability Quality Factor
w_i	Weighting Factor for Property i
P_i^{vir}	Technical Property of the Virgin Material
P_i^{rec}	Technical Property of the Recovered Material
F_i^{vir}	Flow Properties of Virgin Material
F_i^{red}	Flow Properties of Recovered Material
$\alpha_{rec,vir}$	Substitutability of Recovered and Virgin Material
X	Dimensionless Parameter
I_{ideal}	Ideal Value
I_{sample}	Sample Value
I_{min}	Minimum Accepted Value
I_{max}	Maximum Accepted Value
j	Weighting Factor
ξ_i	Decrease in Quality of a Property
ξ_q	Technical Quality Substitutability
MS	Market Share
Q^{rec}	Quality of Recovered Material
Q^{disp}	Quality of Displaced Material
m	Mass
$\eta_{collection}$	Collection Rate
$\eta_{sorting}$	Sorting Efficiency
$I_{Avoided}$	Avoided Impact
I_{Tot}	Total Impact
$S_{Technical}$	Technical Substitutability Coefficient

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1 Introduction

Lately, the focus on society becoming more circular has increased. An important factor in this development is recycling and the use of secondary materials [1]. Recycling keeps the material inside the circular economy, but to increase the field where the secondary material can be used and by that increase the circularity, it is important to have a high quality of the secondary material. A higher quality of the secondary material enables the usage of recycled material in more applications. The quality of the secondary material is a key factor for its usability, and the problems related to the fining of high secondary material are something that concerns the producers that use the material.

Life Cycle Assessment (LCA) is often used as a tool to quantify and evaluate the benefits of recycling. But the benefit of recycling depends a lot on the recycling process itself and which material its output manages to replace [2]. To evaluate the impact, it can be considered that the secondary material can substitute the virgin material to some extent [3]. But when this quantification is made, it must be taken into consideration the potential quality loss from the recycling due to for example contamination and deteriorated mechanical properties. There is no clear way of defining the substitution ratio between the secondary material and the virgin material. Today most of the LCA:s performed on waste management account for a one-to-one substitution ratio, which is an assumption that poorly represents reality and therefore can give a false image of the benefits of recycling [3]. Finding a way to model a substitution rate coefficient is therefore important to make a true analysis of the situation and to provide relevant recommendations.

The glass industry of Europe covers many different types of products and technologies, and the specifics of the productions of these are very diverse depending on the application and product [4]. The container glass sector is the biggest one in the European glass industry [5]. The sector covers the production of different packaging such as bottles and jars for food, drinks, cosmetics, perfume, pharmaceuticals, and other technical products. Regarding volume, the most important product for the sector are bottles for drinks and jars for the food industry.

Glass is an inorganic material that is produced out of inorganic raw materials reacting at a high temperature [6]. In the production of glass, the raw materials are going through both a physical process and a chemical process. In the chemical reaction, the inorganic raw materials are transformed creating a vitreous substance. The physic-chemical properties of glass are therefore dependent on the network that is formed during this process and its composition of elements. A different composition results in a different structure and by that different physic-chemical properties. The major glass-forming material in glass production is silica sand, process cullet, and post-consumer cullet [5]. Apart from that many intermediate and modifying materials as well as coloring and decoloring agents are used in the production.

Glass cullet is broken glass and it can be both generated from the own industry wastes or acquired as external cullet [5]. The importance of glass cullet as a raw material in glass production is increasing, but in some cases, the quality requirements make it hard to get a supplier of cullet that meets the requirement while still being economically feasible. The sorting and recycling process of glass is relatively effective, even though some losses occur mainly because of misidentifications between glass and other materials such as ceramics, stone, and porcelain [7]. A potential loss of circularity occurs due to quality loss in the sorting with other contaminants or packaging materials. In some cases increasing the quality of recycling could be needed to come closer to a circular economy and to get a higher total recycling rate, but a higher-quality recycling is not necessarily better from an economical or environmental point of view than a lower-quality application [8]. However, if the market of lower-quality outputs gets saturated, because of an oversupply, it will most likely create an incentive for the production of higher-quality outputs.

1.1 Aim

The aim of the study is to propose a model for how to deal with the substitution of virgin material with secondary material based on quality parameters, in LCA. The study will develop a substitution model for glass and a way to calculate the substitutability of raw material with secondary glass. The idea is that the model is used in LCA to make the assessment more accurate and by that to create a better understanding of the benefits and drawbacks related to recycling. The model will then be implemented into two case studies to further present its applicability. One study covered the life cycle of a glass bottle, and one study covered the treatment of waste glass.

2

Background

2.1 Circular Economy in The European Union

The European Union (EU) is making a transition towards a circular economy as a part of becoming more sustainable. They adapted one plan for circular economy in 2015 and then a new plan in 2020 [1] [9]. A transition towards a circular economy means that the value of the products, materials, and resources are kept inside the economy for as long as possible and that the generated waste is minimized [1]. The idea is that the transition will gain the EU by for example increasing the competitiveness of the EU and protecting it against a lack of resources. The plan in combination with the legislative proposals regarding waste set the long-term targets of reducing landfilling while increasing reuse and recycling. In a circular economy, the recycled materials are put back into the economy, and secure the supply of material. The secondary material can be treated just like primary resources in terms of shipment and trade.

Secondary raw materials are a relatively small share of the material used in the EU [1]. The main benefits of recycling for the environment are that it enables the replacement of virgin material [8]. But this requires that the quality of the secondary material is sufficient for it to be viable from an economical point of view. And even when the quality is sufficient to replace virgin material, it is commonly not enough to make it economically viable for closed-loop recycling to the same product. In the EU and its member states it has been a major focus on the quantity of recycling in the policies and legislations [8]. Especially, in the Packaging and Packaging Waste Directive where the recycling rate is used as a metric. Instead, the quality of recycling has got less focus even though it is an important factor. Due to the lack of EU standards, it is difficult to establish the impurity levels and whether the materials are suitable for high-grade recycling [1]. Implementation of standards would therefore gain the trust of secondary raw materials and the related market, and because of this EU works on bringing out quality standards.

2.1.1 Waste Management

Waste management has an important role in the circular economy because it determines how the waste hierarchy is applied [1]. The waste hierarchy is creating a prioritization order between different waste treatment options, and it aims to promote the options that have the best environmental outcome. The waste management activities directly affect both the quantity and the quality of the secondary material, so improvement there is of importance.

The waste hierarchy as presented in the EU waste framework directive is as followed:

- Prevention
- Preparing for re-use
- Recycling
- Other recovery
- Disposal [10]

In the framework, it is also stated that the option with the best overall environmental outcome should be favored and that it should be justified by life cycle thinking on the total impact of the generation and management of the waste [10]. LCA is therefore often used for identifying suitable strategies of waste management that limit these negative effects. The thinking of waste is shifting towards being seen as a resource rather than a pollutant, where recycling could save the production of virgin material and recover energy [11]. Therefore several policies and frameworks have been developed to find the best strategies and many of them require the usage of LCA for quantifying the environmental impact.

2.1.2 Circularity of Glass

The circularity of glass depends on many different aspects and varies between countries [7]. Losses in circularity in the glass system take place in the collection stage, the sorting stage, and the distribution stage where the crushed waste glass, also called cullet, is put into different recycling processes and end markets. The major loss in circularity occurs in the stage of collection. The used collection method does not have a large impact on the collection rate, but instead, it has a significant impact on the circular potential of the glass. Some collection systems result in bigger losses than a closed-loop system. Generally, countries using separate collection streams for glass have a higher rate of recycling where the cullet is used in glass manufacturing than countries using a collection system where the glass s collected together with other materials.

A separate collection of glass can either be mixed or separated into different colours [7]. When glass is collected as mixed colour, sorting is needed for clear glass to enable it to be used in the production of clear glass. Most commonly this sorting is not able to collect all clear glass, resulting in material remaining in the amber and green colour. On a local level, this could result in an oversupply of amber and green cullet and a lack of clear cullet for production. Increasing collection rates could lead to the market demand for green and amber cullet being met and that there is no more circular recycling route for the remaining cullet.

Glass collected in a co-mingled system generates a lower fraction of the cullet that is suitable for remelt applications than separately collected glass [7]. Also, because the mingled stream requires more treatment, the particle size of the cullet is reduced. A smaller cullet size makes further sorting from contaminants and based on colour harder, and at a certain point no longer economically feasible. Due to limits on both contaminants and particle size in glass manufacturing, these small cullets will most likely instead be used in other applications.

2.2 Glass

Glass covers a variety of inorganic materials with different compositions and mechanical properties [4]. However, some properties cover all glass materials, such as they all have an amorphous state that comes from the fast cooling from the molten state. A way of classifying different glass types is by their chemical composition, resulting in four different groups:

- Soda-lime glass
- Lead crystal and crystal glass
- Borosilicate glass
- Special glass [5]

Soda lime glass is mainly used in the production of bottles, jars, perfume and cosmetic containers, tableware, and window glass [5]. The wide use of soda lime-glass comes from its physical and chemical properties, such as having a good light transmission and a smooth, non-porous, and chemically inert surface. To produce one tonne of glass it is in general required approximately 1.17 tonnes of raw material, because of the formation of CO_2 during production. The approximate amount of required raw material is as follows:

- 700 kg silica sand
- 192 kg limestone and dolomite
- 207 kg soda ash
- 71 kg of other minerals [4]

2.2.1 The Glass Industry in Europe

The glass-making process requires a lot of capital, and the industry is capital-intensive, which limits the companies entering the market to big enterprises with sufficient financial resources [5]. The market is slowly growing, but even though new furnaces are constructed they are usually built by companies that are already operating in the area or by companies that exist elsewhere that are now entering the area.

The glass industry of Europe can be divided into six different product sectors, these sectors and their approximate share of the total glass production in Europe are as follows:

- Container glass (ca. 56 %)
- Flat glass (ca. 25 %)
- Insulation mineral wool (ca. 10 %)
- Domestic glass (ca. 4 %)
- Special glass (ca. 3 %)
- Continuous filament glass fibers (ca. 2 %) [4]

2.2.1.1 Container Glass

Container glass is normally produced of a soda-lime formulation that is melted in a furnace, usually heated with fossil fuel [5]. When the glass is molten it is usually formed into products by using individual section machines that are automated, and different colouring agents and surface coatings are added to finalize the product.

Typically, the containers, bottles, and jars are not transported more than some hundred kilometers [5]. This is due to the high cost of transportation compared to the sale price of empty containers. This results in more specific local and regional markets for glass containers, especially for alcoholic beverages.

How container glass stands in relation to its competitors on the market varies between different regions and between different products [5]. Its standing depends on several things, such as market preferences, cost, and the development of packaging. Also, the demand for the packaged product affects the market standing of the container glass. An example of this could be if there is a switch in consumer habits towards consuming a lower volume but of higher-quality wine. Another example is different climate factors that might affect the packaged product, such as the wine harvest. Also, the changes in exchange rates between countries and the current financial situation locally will have an impact on the demand for high-value items like perfumes and with that also on the packaging for those products.

2.2.1.2 Insulation Mineral Wool

The sector of mineral wool is representing around 10 % of the total glass production of the glass industry [5]. This sector covers insulating materials of both glass wool and stone wool. These materials consist of masses of fiber with different lengths that are interlaced in a random structure kept together with a binder.

Mineral insulation wool has good thermal properties in combination with good properties regarding acoustic and fire protection, the most important market is therefore the building industry which represents around 70 % of its applications [5]. Glass wool and stone wool can replace each other in most applications but some application requires one instead of the other. For example, stone wool functions better in high-temperature applications and fire protection while glass whole function better when lightweight is an important criterion. There is little opportunity for freedom in the development of fiber insulation products and the competition is therefore mainly based on the price.

2.3 LCA and Glass Recycling

Material recycling is a commonly used waste treatment method that converts waste material and products into secondary material that is used to replace virgin material, and thereby some resources are preserved [2]. The most recycled materials in Europe are glass, metal, paper, cardboard, and plastic. The recycling rate is described as to what degree the material reaches recycling and it varies a lot between different products. Post-consumer waste glass can undergo a recovery process with a recycling purpose to produce products like container glass, flat glass, or insulation mineral wool [4]. These applications require remelting but some applications do not require re-melting like when used as an additive in bricks or ceramics, as filter media, or as abrasive.

The recycling process of glass includes several steps and an example of steps in a typical recycling process is collecting, crushing, sorting, contamination removal, transport, and final use [4]. If there is no final use for the glass it is either stored or disposed. If the glass is being disposed, it is most commonly sent to either landfill or incineration. In the case of incineration, the glass in the bottom ash that remains after the incineration is mixed with other materials and is then either used in applications like civil works or is landfilled.

The environmental and economic benefits of recycling depend on several different aspects [2]. Both the process itself but also on what material production is avoided by the recycling process, and the existing market for the secondary material. To understand if the recycling of material is beneficial it is therefore important to quantify the benefits, and for this, LCA is commonly used. LCA is a methodology defined by the standard ISO 14040 that is used to quantify the environmental burden, benefits, trade-offs, and improvement areas during the lifetime of goods and services [12]. LCA is used in many different fields and can as an example act as support in the creation of public policies. Because of the specific focus of LCA, which often tends to exclude other impacts than environmental, such as the economic and social impacts, it is a tool to support decisions rather than to make them. It is thereby important that it is used as a complement to other tools to detect possible improvements.

2.3.1 The Phases of LCA

LCA has four phases, the first phase is the goal and scope definition which is where the aim is defined in combination with the reasons, conditions, and audience of the study [12]. The main methodological choices are defined as the functional unit and system boundaries, allocation procedures, and impact categories. The second and third phases of the LCA are the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). The LCI consists of the gathering and analyzing of data from activities with environmental contacts, such as emissions, generation of waste, and consumption of resources. The LCIA instead focuses on the estimation of indicators for environmental pressure, such as climate change or acidification. The fourth and last phase is the Life Cycle Interpretation phase. In this phase, the results from the LCI and the LCIA are put in relation to the previously stated goal and scope. In this step, it is checked for completeness, sensitivity, and consistency and it is also dealing with uncertainties and the accuracy of the given result of the study.

2.3.2 Secondary Material from Recycling

The material produced from a recycling process can either be used to produce the same product as the one the material came from, or it can be used to produce something else [2]. The first case is called a closed-loop recycling system while the latter case is called open loop recycling system. In the open loop recycling system, the material does not have to enter the exact same production system, but it must have the same material properties so that it can be added to the stock of material with the same quality as the initial material. Material quality can also degrade during the recycling process which results in the material being unable to replace the initial virgin material. The material can instead replace a material of lower quality or a different material, leading to an open loop recycling system.

Most of the recycled glass cullet comes from container glass or flat glass, but some are also from insulating mineral wool, in this case, the glass has a fibrous structure instead of having the structure of crushed glass pieces [4]. The production of insulation mineral wool is using organic binders, and because of that the waste contains organic material. The presence of organic material can cause problems in the production of new glass materials. Another problem with insulation mineral wool waste is that the waste is usually as composite material which makes it very hard to separate glass and it is therefore very hard to recycle the material into glass products.

Internal cullet comes from defected and rejected products from the industrial production process [4]. The internal cullet can therefore directly be used as a raw material in the same process. Instead, external cullet is collected and reprocessed waste glass. There are two major types of external cullet. The first one is pre-consumer cullet, which is glass that is waste from the production of products containing glass but has never reached the market. The second type is post-consumer cullet, which instead is glass that became waste after it had been used on the market.

The external cullet is limited in its applicability due to uncertainties regarding its composition, and the usage of cullet in the batch formulation is often limited by contaminants in the cullet that is hard to detect and remove [5]. This is especially true for luxury container glass such as, for example, extra-flint bottles for perfume and cosmetics, in these cases the strict product quality requirements limit the usage of external cullet. But, regardless of that, the container glass sector as a whole is using big amounts of external cullet from the bottle recycling schemes.

2.3.2.1 Complications With Glass Cullet as a Secondary Material

When using glass cullet, it must be of sufficient quality for the melting process and the final product, and therefore, the presence of pollutants such as ceramics, glass ceramics, metals, and organic matter needs to be limited or avoided [5]. Different metallic impurities can cause damage and shorten the functional lifetime of the furnace. These impurities can come from for example bottle caps or the foil of wine bottles. What happens is that the metal sinks to the bottom of the furnace and will accumulate and drill into the bottom material. The presence of metals or lead crystal glass can also cause defects in the produced glass.

One of the most problematic contaminants in glass cullet is nonmetal non-glass inorganics [4]. This group includes ceramics, stones, and porcelain (CSP). The reason why this group is problematic is that these materials have a higher melting point and thereby will not melt, resulting in defects in the final product. These materials are also often hard to detect and sort out.

Using a high amount of cullet affects the control of the composition of the glass melt and therefore affects the physical characteristics of the glass, which causes quality issues in the product [5]. Especially the content of organic matter like food, paper, or plastic can affect the oxidation-reduction state. This is especially important in areas that have a high recycling rate, where the contaminants can be accumulated in the recycled material.

In the production of container glass, there are mainly four different colours occurring, these are flint, green, amber, and mixed [4]. The requirements related to the colour of the glass are based on commercial requirements rather than environmental requirements. The accepted limits for colour contaminations, therefore, differ depending on the application and what quality is required by the producer.

For flint glass production, only low levels of other colours are tolerated because it is not possible to decolourise the coloured glass [5]. This is why, to maximise recycling it is required to have either a collection system with separated colours or sorting of the mixed colour collected. In the EU there are many suppliers of coloured cullet, but flint cullet is less common. Therefore, the melting of coloured glass tends to use a higher amount of cullet. This can cause problems of scarcity or excess of the required cullet by regions.

2.3.3 Quality of Recycling

The quality of recycling is a concept that is given a lot of importance and it is mentioned several times in the EU Waste Framework Directive that recycling should be directed towards high quality [10]. Even though the quality seems to be undefined in most scientific articles, and those cases where it is discussed the definitions and approaches are very diverse [13]. The lack of a clear and consistent definition of quality prevents the formation of robust policy measures regarding recycling in the context of a circular economy and limits the possibility to reach a higher resource efficiency.

In the article *Quality of recycling: Towards an operational definition* [14] it is presented a framework for assessing quality and it is also presented some quality categories for packaging material. These categories are based on the key characteristics of the secondary raw material that differentiate how suitable it is for the manufacturing of different products. In the report, the authors also propose the following definition of quality based on the material utility in the circular economy:

"The extent to which, through the recycling chain, the distinct characteristics of the material (the polymer, or the glass, or the paper fibre) are preserved or recovered so as to maximise their potential to be re-used in the circular economy".

These characteristics will differ between different materials, but some examples that are mentioned are food-contact suitability, structural characteristics, clarity, colour form, and odor [14].

2.3.3.1 Quality Aspects of Glass Cullet

The quality of glass cullet, its value, and possible endpoint application depends on its physicochemical composition, its colour, the composition of impurities, and the homogeneity within its specifications [14].

The colour of the glass product cannot be recovered after being contaminated [14]. Therefore, to produce clear glass, it is required to use clear cullet with a very low amount of coloured cullet present. Amber glass tolerates higher levels of colour contaminants and can be produced with the presence of some green and clear glass cullets. Green glass production tolerates even larger amounts of contamination from other colours. Therefore, glass cullet that is separated into clear or amber tends to have a higher value. While the mixed glass cullet is more limited in its usability but can be used in non-colour specific products as insulation material.

The presence of contaminants causes problems in the remelt process [14]. Ferrous and organic materials can cause coloration of the glass. Instead, non-ferrous materials can cause defects in the products and damage the furnace. The presence of other materials like ceramics, porcelain, stones, and pyro-ceramics can cause defects in the final product because of their higher melting point.

Container glass consist of only soda lime glass, therefore the presence of other glass types with other physicochemical compositions can cause problems in the manufacturing [14]. Ideally, for the quality of the container glass cullet, it should therefore only consist of soda lime glass.

2.3.3.2 Quality Categories for Glass Cullet

In the article *Quality of recycling: Towards an operational definition* it is presented different quality categories for container glass cullet [14]. The stated categories were based on the required quality aspects of glass cullet used in different end-use applications. The presented categories were scaled from A-E. Category A took into consideration all three quality aspects and was considered fully circular and suitable for container glass manufacturing. Instead in category B, the aspects of contaminants and physicochemical type were considered and the category would be suitable for darker colour container glass, other remelt market, or abrasives. Category C-E only considered the aspect of contaminants, where C had specific restrictions, D had overall restrictions and E had a high tolerance. Category C was considered suitable for overall non-remelt applications while D was considered suitable for some non-remelt applications and category E was considered suitable as aggregate. A summary of the presented categories from the article can be seen in the table 2.1.

Table 2.1: Quality categories presented in the article Quality of recycling: Towards an operational definition [14]

Category	Quality aspect	Application
A	• Color • Specific contamination limits • Physicochemical type	• Colour specific container glass
B	• Specific contamination limits • Physicochemical type	• Darker colour container glass • Remelt applications • Abrasive
C	• Specific contamination limits	• Non-remelt applications
D	• Overall contamination limits	• Some non-remelt applications
E	• High tolerance for contaminants	• Aggregate use

Remelt applications require high levels of purity of the material [8]. Between remelt applications, there are relatively small differences in terms of the quality requirements of purity, even though tolerance levels may differ a bit between the individual contaminant between the applications. So, the major varying factor between the remelt applications in terms of quality seems to be the colour preservation.

2.3.4 The Multifunctionality of Recycling

Multifunctionality means that the process provides more than one function [11]. Recycling can be seen as both a waste management process and a material production process [2]. Because of this the recycling process is shared between different product systems and is therefore a multifunctional process. For multifunctional processes, it is not always clear how to assign the environmental impacts between the processes.

One way of dealing with multifunctional processes is by using system expansion [3]. System expansion could mean adding non-provided functions to the system to make the system comparable, but there is also a variation of system expansion called substitution [15]. When using substitution, functions are subtracted from the system, and this is done by considering what function they can replace. To do so is necessary to identify an external mono-functional process that provides products or functions that are equal to the products from the multifunctional process [3]. The inventories of the mono-functional process can then be subtracted from the multifunctional process to evaluate what inventories that are associated with the studied co-function.

A major problem when using substitution as a method is to quantify to what degree the product is equal in functionality and to what degree they are substitutable [3]. In the quantification of the replaced virgin material by the secondary material, it must be kept in mind that the secondary material might have gone through a reduction in quality (downcycling). The reasons for downcycling could be many, for example, the breakdown of mechanical characteristics in the recycling process, or cross-contamination with other materials caused in the collection and sorting phase. Even though this would have an impact on the substitutability, most of the LCA studies performed on waste management instead assume a one-to-one (1:1) substitutability ratio between the recycled material and the virgin material. This assumption means that the secondary material is functionally equal and can fully replace the virgin material. This assumption could lead to incorrect conclusions and advice.

2.4 Substitutability Models

Quantifying to what degree products are functionally equal and can substitute each other is not easy, but it is of importance because it can influence the results of the LCA [3]. In the Product Environmental Footprint (PEF) guide there is included a ratio between the quality of primary and secondary material [16]. The ratio should either be based on economical or physical aspects depending on the relevance and determined at the point where the substitution occurs and for each application or material.

Different approaches have been suggested by different authors to calculate substitutability, both based on market and technical functionality. Both approaches have their drawbacks, but models regarding technical functionality is more commonly used in LCA, cause of the lack of data availability and fluctuation in market prices causing inconsistent results [17]. But even though physical parameters are not determined by economic fluctuations, they are seldom used cause of the difficulty of determine quality factors for specific waste types based on physical parameters [3].

2.4.1 Substitution Potential

Vadenbo et al.[18] introduced a framework for calculating the substitution potential based on the physical resource potential U_{rec}, the resource recovery efficiency η_{rec}, the substitutability $\alpha_{rec,disp}$ and the market response π_{disp}. Their expression for the substitution potential was then:

$$\gamma = U_{rec} \times \eta_{rec} \times \alpha_{rec,disp} \times \pi_{disp} \tag{2.1}$$

The article did not provide guidance on how to determine the market response since it was considered to be one for all the presented cases [18]. Instead, the introduced substitutability term was defined as the degree of functional equivalence between the recovered material ϕ_{rec} and the displaced material ϕ_{disp} for a specific application.

$$\alpha_{rec,disp} = \frac{\phi_{rec}}{\phi_{disp}} \tag{2.2}$$

2.4.1.1 Technical Properties

Rigamonti et al. [3] suggested a guide based on the framework of Vadenbo et al. [18] on how to determine the technical substitutability coefficient based on one technical property. The suggested guide consists of the identification of the functionality of the secondary material based on application and the identification of the substituted material in the considered application. Then the guide suggests identifying the main technical property (TP) that is necessary for the key functionality and quantifying it both for the secondary material ($TP(SecM)$) and the substituted material ($TP(SubM)$). The ratio between the technical properties is then the technical substitutability coefficient (TSC).

$$TSC = \frac{TP(SecM)}{TP(SubM)} \tag{2.3}$$

Instead of using one technical property Demets et al. [19] presented a concept of calculating the technical substitutability of plastic based on two recycling quality factors. One that deals with mechanical requirements for a specific application and one that deals with the processability of the plastic. The mechanical quality factor (RQ^{mech}) was considering several mechanical properties for a specific application. The quality factor was then determined as the weighted sum of the scoring functions for each property. The processability quality factor was instead determined by a function based on relevant flow properties. The overall substitutability coefficient for a specific application was then determined by the minimum value of the two quality factors.

$$RQ^{mech} = \sum_{i=1}^{n} w_i \times f(\mathrm{P}_i^{vir}, \mathrm{P}_i^{rec}) \tag{2.4}$$

$$RQ^{proc} = f(\mathrm{F}_i^{vir}, \mathrm{F}_i^{rec}) \tag{2.5}$$

$$\alpha^{rec,vir} = \min\left[RQ^{mech}, RQ^{proc}\right] \tag{2.6}$$

Also, Golkram et al. [20] presented a quality model for recycled plastic that consider a wide range of properties, such as mechanical, processability, odour and colour. In their model, a dimensionless parameter is calculated for each property based on the allowed interval of that property and the difference between the ideal case and the sample of the recycled plastic.

$$X = \frac{I_{ideal} - I_{sample}}{I_{min} - I_{max}} \tag{2.7}$$

The interval $I_{min} - I_{max}$ was the total accepted interval for all the considered secondary applications [20]. And hence, if the value for the sample is outside the range $I_{min} - I_{max}$ then the technical quality is set to 0. Their model is also using a weighting factor j for the relevance of the different characteristics. The decrease in quality for each individual factor they then expressed as:

$$\xi_i = \frac{1}{(1 + |X_i|)^j} \text{ for } \xi_i < 1 \tag{2.8}$$

They then defined the technical quality substitutability as:

$$\xi_q = \prod \xi = \xi_1 \times \xi_2 \times \xi_3 \times \xi_4 \times \xi_5 \tag{2.9}$$

2.4.1.2 Applicability

Instead of using technical properties Eriksen et al. [21] used market shares and applicability to evaluate the difference in functionality between recovered plastic and virgin plastic. Their suggested model for substitutability was based on the division of applications into three quality categories, high, medium, and low. The market shares of the quality categories were then determined. So, the quality of the secondary material determines its applicability. The functionality is therefore defined by the applicability and the potential to fulfill a demand in a steady-state market. They thereby determine the substitutability as the division between the functionality of the recovered material and the virgin material as presented in Vadenbo et al. [18].

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$$\alpha^{rec,disp} = \frac{MS(Q^{rec})}{MS(Q^{disp})} \tag{2.10}$$

2.4.1.3 Technical Properties and Applicability

Horodytska et al. [22] discuss modifications that can be made in the modeling of the substitution coefficient to adapt it to the needs of the circular economy. The technical substitutability is going to be higher for a lower-quality application due to lower requirements. Therefore, the substituted material in the study is calculated by multiplying the substitution rate with the market share to also evaluate the loss in circularity and potential applicability.

Huysveld et al. [17] instead presented a way of calculating the overall substitutability of plastic by multiplying the market substitutability and the technical substitutability to consider both the material quality degradation and the difference in market size caused by legislative restrictions. For calculating the technical substitutability, they used a simplified version of the mechanical quality factor presented by Demets et al. [19]. The market substitutability was instead based on the model presented by Eriksen et al. [21] and determined by the market share that could be targeted by the material from a legislative point of view. In the model, only the technical substitutability is calculated based on a specific application.

$$TS = \sum_{i=1}^{n}(w_i \times \frac{P_{i,rec}}{P_{i,vir}}) \tag{2.11}$$

3
Methods

The methodology of the study was divided into three major parts. The project started with a literature review regarding the current situation in the field of substitution models between secondary material and virgin material. Out of this, a concept for how to deal with quality degradation and substitution between secondary material and raw material from recycling in LCA was decided. This was based on the information found in the previous literature review. The second step was then to adapt and form the model for a secondary material. To do so, another literature review and data gathering was made to collect information about the secondary material. The model was then formed based on the collected information. The third part of the project consisted of the construction of two case studies and the implementation of the model to demonstrate and evaluate its performance. An overview of the different parts of the project is presented in figure 3.1 below.

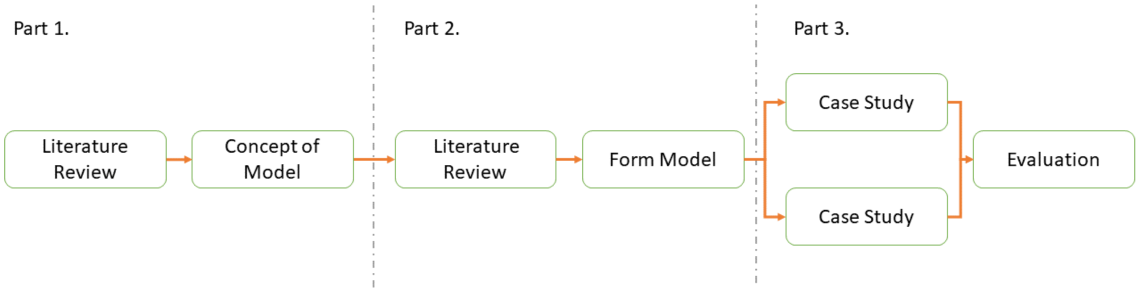

Figure 3.1: Illustration of the methodological process of the project

3.1 Literature Review Substitution Models and Quality

The main focus of the first literature review was to understand the current situation in the field regarding models for substitution coefficients for the substitution between virgin raw material and secondary material. The focus was mainly to find articles from 2020, but also older articles was included. This decision was made because the study took its base in the article *A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies*[3] that was released at that time. The major findings regarding existing substitution models are presented in section 2.4. Apart from that, the literature review also focused on the definition of quality, recycling, and quality of secondary materials. The data search was performed using mainly databases and examples of the keywords used in the search were *"substitution coefficient"*, *"quality secondary material"* and *"quality degradation recycling"*. Some examples of databases that were used during the literature review were ScienceDirect, SpringerLink, and Wiley online library.

3.2 Concept of the Model

The model was based on the information found in the literature review. Different aspects of what is important to consider in the evaluation of quality degradation and how well secondary material can substitute raw materials from the literature review were analyzed. When using system expansion for dealing with the multifunctionality of recycling, the avoided impact is calculated from the replaced virgin material. What virgin raw material is replaced depends on in what application the secondary material is used. What application it is used in, depends on both the technical quality of the secondary material and the market for that application. Because of this, the model was formed based on these three concepts, and the formation of quality categories to evaluate the quality of the material. Also, as found in the literature review there are many existing substitution models for plastic. Instead, no developed model was found for glass. Glass is an important and widely used secondary material with a high recycling rate in Europe. And therefore, the decision was taken to adapt the model for glass.

Most of the substitution models found take their base in the concept presented by Vadenbo et al. (2017) [18] and focus on differences in functionality between the virgin and raw material. Some focus on technical properties and some focus on applicability and some on both. The decision was therefore made to evaluate both aspects in this model. To do so both a Technical Substitution coefficient based on the concept presented by Golkram et al. [20]. and a market substitution coefficient based on the concept presented by Eriksen et al. [21] were included in the model. To consider the distribution between different applications the market share was used.

3.3 Substitution Model for Glass

The substitution model for glass was then formed by determining quality categories for glass cullet and then adapting the considered methods of determining the technical substitution coefficient and the market substitution coefficient for those categories.

3.3.1 Quality Categories

The quality categories that were chosen for the model for glass were based on the presented categories in the article *Quality of recycling: Towards an operational definition* [14]. In the article, five quality categories (A-E) for container glass cullet were presented, but only category A and B includes cullet that replaces glass as virgin material. Therefore, only categories A and B were considered in the formation of the quality categories of this model. In the article, three major quality aspects of glass cullet were presented. However, to simplify the formation of the model and because of a lack of data found regarding the physicochemical type, only colour and impurities were considered as key quality characteristics.

Some secondary applications were mentioned related to the quality categories in the article. For category A, were mentioned container glass of the same colour, while for category B were mentioned secondary applications such as container glass of darker colour, insulation material, and abrasive. It was noted that the application of container glass for both categories A and B enables further recycling of many loops while the application insulation material is limited in recyclability and the use as abrasive does not enable any further recyclability. To try to take the differences between the applications into consideration in the development of the model, category B was divided into two subcategories. One for container glass of darker colour (B:1) and one for insulation material (B:2), while abrasive were not considered for simplification reasons.

3.3.2 Literature Review and Data Collection for Glass

A literature review was made to find information regarding glass as a secondary material, its quality aspects, and key characteristics in different secondary applications. The literature review was performed in a similar way as the previous one, mainly using databases like ScienceDirect, SpringerLink, and Wiley online library in the information search. The search took its start in the information regarding the quality of glass cullet found in the article *Quality of recycling: Towards an operational definition* [14], and the search was then expanded from there. The search was mainly performed looking for secondary applications, key characteristics of these applications, and allowed limits for these characteristics. Some examples of keywords that were used in the searching process were *"quality glass cullet"*, *"contamination limits glass cullet"* and *"quality characteristics secondary glass"*.

Different companies and organisations related to the glass and recycling industry were contacted through email and some online meetings were performed to complement the data found in the literature review. Questions that were asked were mainly regarding contamination limits and colour limits for the considered applications. Also, a plant visit to the Eurovetro sorting plant located in Origgio, in northern Italy was performed as a part of the information gathering.

The result of this study is partially presented in the background section for a further understanding of glass as both a primary and secondary material. However, the major result of the study is shown in the forming of the quality categories based on applications as well as the quality factors and accepted intervals for the categories. The collected data regarding the accepted impurities and colour contaminants are presented in table 3.1 and 3.2.

Table 3.1: Limits on impurities in glass cullet

Organisation/ Standard	**Fe metals (ppm)**	**Non-Fe metals (ppm)**	**Nonmetal non-glass inorganic, CSP (ppm)**	**Organic (ppm)**	**Heavy metals (ppm)**
End of waste criteria for glass cullet[a]	50	60	100	2000	-
FERVER [a]	10	60	100	2000	-
Eurima [a]	10	20	25	3000	-
Packaging material recycling CEN/TR 13688:2008 [b]	5	5	50	500	-
Packaging directive [c]	-	-	-	-	200
BV Glas standard sheet T 120 [d]	5	5	50	500	200
Industrial specifications Italy	10	20	35	500	-
Company in the container glass sector	2	3	20	300	-
Company in the insulation sector	5		20	500	-

The data is from E. Rodriguez Vieitez, P. Eder, A. Villanueva Krzyzaniak, and H. Saveyn [4][a], SIS/TK 165 [23][b], European Commission [24][c], and Bundesverband Glasindustrie e.V. (BV Glas), Bundesverband der Deutschen Entsorgungs-, Wasser- and Rohstoffwirtschaft e.V. (BDE), Bundesverband Sekundärrohstoffe and Entsorgung e.V. (BVSE) [25][d].

Table 3.2: Limits on colour contamination in glass cullet

Organisation/ Standard	Flint	Amber	Green
Company in the container glass sector	> 99% Flint	> 80% Amber	> 75% Green
Company in the container glass sector	≥ 99% Flint < 0.2% Amber < 0.2% Green < 0.2% Blue	≥ 90% Amber < 5% Flint < 5% Green	≥ 90% Green < 5% Flint < 5% Amber
Packaging material recycling CEN/TR 13688:2008 [a]	> 98% Flint < 1% Amber < 1% Green	> 82% Amber < 8% Flint < 10% Green	> 85% Green < 15% Flint < 5 Amber
BV Glas standard sheet T 120 [b]	< 0.3% Amber < 0.2% Green < 0.2% Coloured	≥ 80% Amber < 10% Green	≥ 75% Green < 10% Amber
BSI/WRAP PAS 101 [c]	> 94 % Flint	> 85 % Amber	> 70 % Green
FERVER [c]	> 98 % Flint	-	-

The data is from SIS/TK 165 [23][a], Bundesverband Glasindustrie e.V. (BV Glas), Bundesverband der Deutschen Entsorgungs-, Wasser- and Rohstoffwirtschaft e.V. (BDE), Bundesverband Sekundärrohstoffe and Entsorgung e.V. (BVSE) [25][b], and E. Rodriguez Vieitez, P. Eder, A. Villanueva Krzyzaniak, and H. Saveyn [4][c].

3.3.3 Technical Substitutability for Glass

The model for technical substitutability that was presented by Golkram et al. [20] was adapted for glass. In order to use this framework to form a model for the technical substitutability of glass, it had to be adapted to the considered quality aspects and formed quality categories for glass.

3.3.3.1 Quality Factors and Weighting

Based on the data and information found in the literature review the key quality aspects were further divided into different quality factors of importance for the quality of the glass cullet for the different quality categories. The two key aspects were given the same weighting because no information regarding the relative importance between the categories was found. In the case of colour, this category was not considered for category B:2 because it is a less important characteristic for the application of that category. The category regarding impurities was divided into five quality factors for categories A and B:1 and four quality factors for category B:2. Each of the quality factors in each of the subcategories was given the same weighting because of a lack of information regarding their relative importance.

A summary of the considered aspects and factors for the different categories is shown in table 3.3 and table 3.4.

Table 3.3: Considered quality factors and weighting for category A and B:1

Factors	Weighting
Impurities	**0.5**
Fe	0.1
Non-Fe	0.1
Inorganics	0.1
Organics	0.1
Heavy metals	0.1
Colour	**0.5**
Other coloures	0.5

Table 3.4: Considered quality factors and weighting for category B:2

Factors	Weighting
Impurities	**1**
Fe	0.25
Non-Fe	0.25
Inorganics	0.25
Organics	0.25

3.3.3.2 Intervals

The accepted intervals were evaluated based on the data found on the limits of contaminants and colour for the different applications considered in the quality categories. The limits for the intervals were built on the collected data that can be found in 3.1 and 3.2. Two extreme cases were created from the data by focusing on the extreme values found for each quality factor. This resulted in one case with the highest tolerance possible and one with the lowest tolerance possible. This decision was made due to that the data found for the allowed intervals varied a lot between different sources. Because each key category was assumed to consider contaminants, the ideal value for each of the factors was zero.

3.3.4 Market Substitutability and Market Shares

According to the information found in the literature study, the demand for glass cullet in all the considered categories is high and the secondary markets for glass cullet are functional. Therefore, the market substitutability for glass was assumed to be one. The market shares for the different quality categories were determined based on collected data regarding the production amount and market share of the considered applications.

In the model, categories A and B:1 are represented by container glass while category B:2 is represented by insulation wool. The market share for the different categories was therefore determined by the market share of the different applications in relation to each other. The market share for container glass and insulation wool was based on data found regarding their fraction of the total market share for glass. Based on this, these values, the market shares for container glass and insulation wool in relation to each other were calculated as follows:

$$MS_{Contianer} = \frac{MS_{tot,container}}{MS_{tot,container} + MS_{tot,insulation}} \tag{3.1}$$

$$MS_{Insulation} = \frac{MS_{tot,insulation}}{MS_{tot,container} + MS_{tot,insulation}} \tag{3.2}$$

The received values were confirmed as realistic by two different industry contacts.

Since both categories A and B were covered by the market share of container glass their respective fraction was calculated based on the produced share of colourless and coloured container glass in Europe in 2020. The share of colourless and coloured container glass was calculated as follows:

$$MS_{Colourless,container} = \frac{Production_{Colourless,container}}{Production_{Colourless,container} + Production_{Coloured,container}} \tag{3.3}$$

$$MS_{Coloured,container} = \frac{Production_{Coloured,container}}{Production_{Colourless,container} + Production_{Coloured,container}} \tag{3.4}$$

The market share for category A and B in the model were then defined as follow:

$$MS_A = MS_{Container} \times MS_{Colourless,container} \tag{3.5}$$

$$MS_{B:1} = MS_{Container} \times MS_{Coloured,container} \tag{3.6}$$

$$MS_{B:2} = MS_{Insulation} \tag{3.7}$$

3.4 Case Studies

To demonstrate the applicability of the developed model two case studies were created to evaluate its impact and study its functionality. The first developed case was created to represent a general case for the life cycle of a glass bottle in Europe. While the second case represented a general European case for the treatment of waste glass.

3.4.1 Case Study, Glass Bottle

3.4.1.1 Goal and Scope Definition

The goal of the case study was to determine the environmental impact of a glass product, and the study aimed to evaluate the change in environmental impact when an aspect of material quality degradation from recycling was considered instead of a substitution ratio of one to one (1:1).

The functional unit of the system was set to a container with a weight of 450g. The system considered a cradle-to-grave life cycle of a glass bottle, and the system included the production of the glass bottle as well as the collection and end-of-life treatment. However, the use phase of the bottle was not considered. Only the glass material of the bottle was considered and therefore no accounts for additional materials in the form of caps or labels were considered. The considered system was assumed to take place in Europe, so European conditions were considered in the data collection. An overview of the system flowchart is presented in figure 3.2.

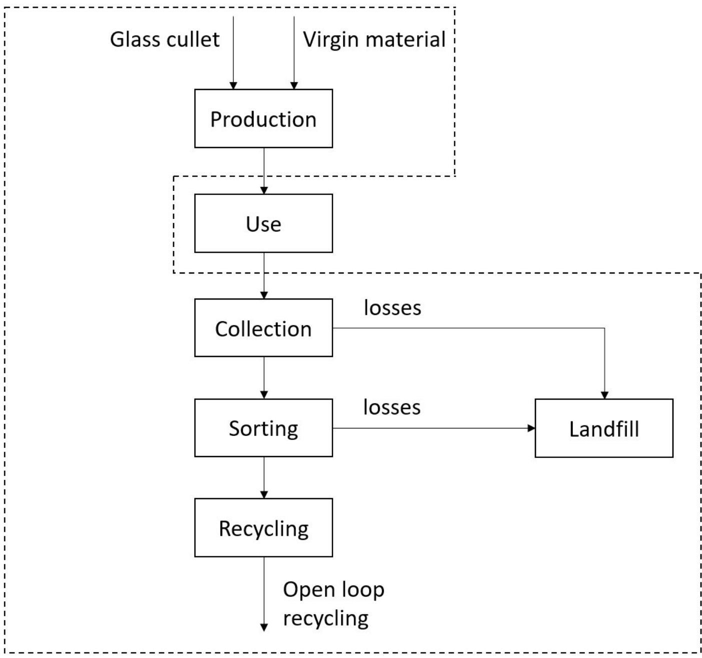

Figure 3.2: Flowchart of the considered system of the glass bottle

3.4.1.2 Material Flow Analysis and Inventory Analysis

To determine and evaluate the material flow through the system a material flow analysis was performed. The mass flow in point one (m_1), represents the mass of the functional unit. Then some losses of material occur during the usage phase and not all the produced glass is collected for recycling. The material flow in point two (m_2), is therefore calculated as the mass flow in point one (m_1) multiplied by the collection rate ($\eta_{collection}$). The material that is not collected for recycling (m_3) is assumed to go to landfill. The material that is collected for recycling is treated in the sorting process, and there occur some material losses in the sorting plant. Therefore, the material flow in point four (m_4) was calculated by multiplying the collected material (m_2) with the sorting efficiency ($\eta_{sorting}$) of the plant. The material flow in point four (m_4) was assumed to be available for recycling. The calculations made determining the flows in the different process stages are shown in table 3.5.

Table 3.5: Calculations of mass flow in each process stage of the case of the glass bottle

	Process stage	**Calculations**
1	Produced flint container glass	m_1
2	Container glass collected for recycling	$m_1 \times \eta_{collection}$
3	Container glass sent to landfill	$m_1 \times (1 - \eta_{collection})$
4	Sorted cullet available for recycling	$m_2 \times \eta_{sorting}$

For the inventory of the system, a combination of data and information found in literature and data from the Ecoinvent database [26] were used. A glass bottle of the functional unit was assumed to have a weight of 0.45 kg based on similar studies made [27] [28].

For the production of the bottle under European conditions, the process *"Packaging glass, white RER w/o CH+DE| production | Cut-off, U"* from the Ecoinvent database [26] was considered. This process was chosen because it uses a mix of cullet and virgin raw materials, and it is adapted to represent European conditions. The collection rate of container glass for recycling in Europe was considered to be 76 % [29].

For modeling the sorting and processing of the cullet the process *"Glass cullet, sorted RER| treatment of waste glass from unsorted public collection, sorting | Cut-off, U"* from the Ecoinvent database [26] was used. The recovery rate is then assumed to be 92.5 % and the remaining fraction is losses of glass and scrap that were sorted out in the process. The share of the glass that was not collected for recycling was instead assumed to go landfill. For this, the process *"Waste glass GLO| treatment of waste glass, sanitary landfill | Cut-off, U"* from the Ecoinvent database [26] were used.

The transportation of the material between the processes was assumed to occur using trucks and the process *"Transport, freight, lorry 16-32 metric ton, EURO5 RER| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U"* from the Ecoinvent database [26] was used for modeling it. Transportation was assumed to take place between the collection place and the sorting plant as well as between the collection and the landfill. Also, transportation was assumed to occur between the sorting plant and the place for recycling. The average distance for transportation of secondary material and waste material in Europe was 73.5 km [30]. This amount was therefore used in all the above transportation cases. The output from the sorting plant was assumed to have the characteristics as presented in table 3.6.

Table 3.6: Amount of impurities and colour contamination in the output sample

Impurities	**(ppm)**
Fe metals	0.5
Non-Fe metals	0.5
Inorganics	17
Organics	350
Lead	10
Colour	**(%)**
Flint	15
Amber	5
Green	80

The values were based on information received in contact with a company as normal contamination values for the cullet they receive in combination with information from Eurovetro.

3.4.1.3 Impact

The considered impact category in the study was climate change and the considered indicator was Global Warming Potential (GWP100). For analysing the impact of the system, the "EF 3.0 Method (adapted) V1.02 / EF 3.0 normalization and weighting set" in Simapro was used. To evaluate the impact of sorting and recycling, system expansion by substitution was used. The avoided burden from avoided production due to replacement with secondary material was therefore evaluated.

The total impact of the system is then the impact of the process plus the impact of the transport to recycling minus the avoided impact from the avoided production of the materials that are substituted.

$$I_{Avoided} = I_{Rawmaterial} \times m_{sub} - I_{Transportrecycled} \times m_4 \tag{3.8}$$

$$\begin{aligned} I_{Tot} = I_{Prod,Flint} \times m_1 + (I_{Transportsorting} + I_{sorting}) \times m_2 \\ + (I_{Transportlandfill} + I_{landfill}) \times m_3 - I_{Avoided} \end{aligned} \tag{3.9}$$

3.4.1.4 Substituted Material

The avoided burden depends on what the avoided production is. In this model, the recycled glass cullet was assumed to be used in the production of new glass products. Hence all the considered categories represent a substitution of raw material for virgin glass. The composition of raw materials in the virgin glass was assumed to be 61 %

silica sand, 18.5 % soda-ash, 2 % feldspar, 6 % dolomite, and 12.5 % limestone. The composition was based on data from the Ecoinvent database [26], the end of waste criteria [4], and data from Coreve [31] 1 kg of cullet were assumed to replace 1.17 kg of raw material due to emissions in the melting process. The following processes from the Ecoinvent database [26] were used to calculate the impact from virgin glass:

- *"Silica sand GLO| market for | Cut-off, U"*
- *"Soda ash, light, crystalline, heptahydrate GLO| market for | Cut-off, U"*
- *"Feldspar GLO| market for | Cut-off, U"*
- *"Dolomite RER| market for dolomite | Cut-off, U"*
- *"Lime RER| market for lime | Cut-off, U"[26]*

3.4.1.5 Substituted Amount of Material

A base scenario and two cases were formed for the calculation of the substituted amount of raw material. The base scenario represented a case where the quality degradation of the material was not considered so a one-to-one (1:1) substitution ratio regarding quality was assumed. The substituted amount of raw material was then calculated as follows:

$$m_{sub,1:1} = m_4 \times 1.17 \tag{3.10}$$

Instead in Case 1 and Case 2, the quality degradation was considered, and the developed model was implemented. Case 1 represented a scenario where the quality requirements and limitations for the considered categories were more tolerant while Case 2 represented a less tolerant scenario.

The cullet was assumed to be used as a raw material in new glass production for different applications in different categories. The quality requirements therefore differ between the category. To determine the division of the cullet between the quality categories, the quality requirements and the market shares of the categories were used.

The secondary glass market was as mentioned before considered to be stable and functioning for all categories. The market substitutability was therefore put to one. The assumption that there is a request for secondary material in all the categories was therefore made. The division between the categories was therefore created based on the relative market share of the categories. However, in the case of downcycling, higher-quality applications will be preferred over lower-quality applications unless saturated. To demonstrate the effect of using market substitutability different than one a saturated version was calculated for each of the cases.

Case 1 less tolerant substitution
The technical substitution coefficient for each of the categories was calculated based on the sample values of the less tolerant intervals. The division of the material between the quality categories was determined based on the quality requirement of

the categories and the market shares. In this scenario the sample value did not fulfill the requirements for category A and B:1. Therefore, all the recycled material were treated according to category B:2. The substituted amount of raw material was then calculated as follow:

$$m_4 = m_A + m_{B:1} + m_{B:2} \tag{3.11}$$

$$m_A = m_{B:1} = 0 \tag{3.12}$$

$$m_{B:2} = (MS_A + MS_{B:1} + MS_{B:2}) \times m_4 \tag{3.13}$$

$$m_{sub,B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.14}$$

$$m_{sub,tot} = \sum_{i=1}^{n} m_{sub,i} \tag{3.15}$$

Saturated conditions Case 1
Considering that the market of the lower-quality categories would be saturated for this scenario, these categories can not be targeted by a higher share than their assigned market share. The sample can only target category B:2, so if that category's capability to use material is limited the substitution will be limited to that amount.

$$m_{B:2} = MS_{B:2} \times m_4 \tag{3.16}$$

$$m_{sub,tot} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.17}$$

Case 2 more tolerant substitution
In this scenario, the technical substitution coefficient was calculated for each of the categories based on the sample values as for case 1 but instead using more tolerant intervals in the model. Also, the division between the quality categories was based on the more generous quality requirements and the market shares. In this more tolerant scenario, the sample value fulfilled the requirements for both category B:1 and category B:2 but not for category A. The material was therefore divided between the categories according to their respective market share, but the share of category A was instead placed in category B:1. The substituted amount of raw material was then calculated as follows:

$$m_4 = m_A + m_{B:1} + m_{B:2} \tag{3.18}$$

$$m_A = 0 \tag{3.19}$$

$$m_{B:1} = (MS_A + MS_{B:1}) \times m_4 \tag{3.20}$$

$$m_{B:2} = (MS_{B:2}) \times m_4 \tag{3.21}$$

$$m_{sub,B:1} = 1.17 \times S_{Technical,B:1} \times m_{B:1} \tag{3.22}$$

$$m_{sub,B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.23}$$

$$m_{sub,tot} = \sum_{i=1}^{n} m_{sub,i} \tag{3.24}$$

Saturated conditions Case 2
In this scenario, the sample can target both category B:1 and category B:2. If these categories were considered saturated then the amount of material that could substitute material would be limited to these categories' capability to take up the material.

$$m_{B:1} = MS_{B:1} \times m_4 \tag{3.25}$$

$$m_{B:2} = MS_{B:2} \times m_4 \tag{3.26}$$

$$m_{sub,B:1} = 1.17 \times S_{Technical,B:1} \times m_{B:1} \tag{3.27}$$

$$m_{sub,B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.28}$$

$$m_{sub,tot} = \sum_{i=1}^{n} m_{sub,i} \tag{3.29}$$

3.4.2 Case Study, Waste Glass Treatment

This case was formed to demonstrate the impact that the substitution coefficient can have in the evaluation of a waste treatment system. The case was partially formed from information given by Eurovetro and partially formed by information found in literature and the Ecoinvent database [26].

3.4.3 Sorting Plant

The Eurovetro sorting plant located in Origgio in the north of Italy treats approximately 300 000 tonnes of packaging glass per year. The main objectives of the sorting operations are separation from extraneus fractions such as metals and plastics, and removal of infusible materials like ceramics, and sorting by colour. There is also a separation from lead glass, since there is a limit on heavy metals for the food industry in Europe of 200ppm. The plant is equipped with optical sensors for these objectives.

The layout of the plant starts with a mechanical and manual pre-sorting phase where metals are sorted out with magnets and Eddy Current Separators (ECS) and coarse and bulky waste are separated by hand. After the pre-sorting phase, a particle size homogenization (sieving) is made. It is then dried in a fluidised bed dryer in order to remove organics and make the glue melt. A screw is used to remove the labels and caps by friction.Sieving is made to remove the fine fractions of glass. Cullet with a size of < 3 mm can not be properly separated from infusible material or ceramics by the optical sensors because of the small size and can therefore not be used by glass recyclers. There is no end of waste criteria making it a secondary raw material and it is therefore treated as waste. Metals are removed using magnets and a screening to separate material smaller than 10 mm. Three steps of optical selectors are performed removing infusible materials, metals, and lead glass. And for the stream with a size > 10 mm three steps of optical selectors are performed, based on light colour removal, dark colour removal, and the separation between white and half-white.

Of the input of the sorting plant, approximately 85 % is glass that can be delivered to recyclers, and around 8 % ends up in a stream of fine fractions with a size less than 3 mm. Approximately 4 % are metals and 3 % are other types of waste that are sorted out. The fine fraction glass stream is sent as waste to the building industries. Cullet with a size less than 10 mm can not be separated by colour by the optical sensors and therefore consist of a mix of colours. The colour separation output of the plant is white, half-white, and green and amber combined. The half-white has a light blue or green reflection making it not completely clear, which is requested by some customers mostly because of marketing reasons. The four final products of the sorting plant and their approximate output share are white cullet (12 %), half-white cullet (4 %), cullet of darker colour (42 %), and cullet of mixed colour (42 %). The different output products can be seen in figure 3.3 below.

A. B. C. D.

Figure 3.3: Output products from the glass sorting plant, A: White, B: Half-White, C: Dark, D: Mixed

3.4.3.1 Goal and Scope Definition

The goal of the study was to determine the environmental impact of the treatment of waste glass. While doing so the study aimed to evaluate the change in impact when the aspect of quality degradation of the secondary material was considered in comparison to a one-to-one (1:1) substitution ratio.

The functional unit of the system was set to the treatment of 300 000 tonnes of waste packaging glass. The system considered the transport of the collected glass waste and the sorting process of the stream. The considered system was assumed to take place in Europe under European conditions. An overview of the system flowchart is presented in figure 3.4.

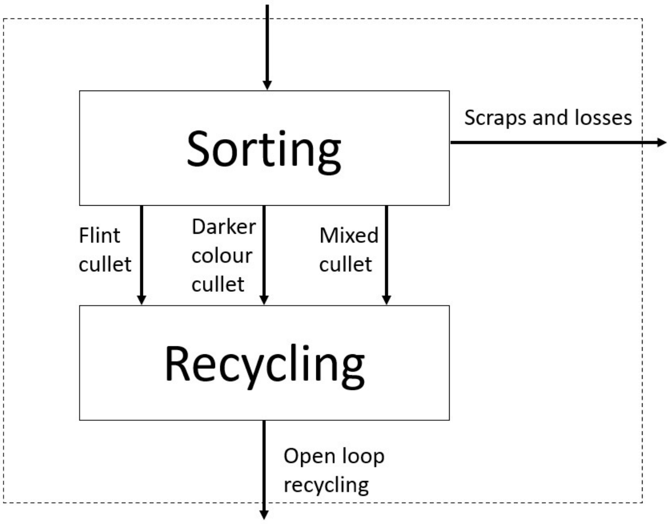

Figure 3.4: Flowchart of the considered system of waste glass treatment

3.4.3.2 Material Flow Analysis and Inventory Analysis

In the same way, as in the case of the glass bottle, a material flow analysis was performed to understand the flow of material through the system. The mass flow in point (m_1) one represented the functional unit. Then the mass flow in point two (m_2) represented the total output of cullet after the sorting. The amount of each output product was calculated based on the ratio of each product in the output x_i. For the created system three product streams were considered, these were flint cullet (m_4), darker coloured cullet (m_5), and mixed cullet (m_6). The calculations determining the flows in the different process stages are shown in table 3.7.

Table 3.7: Calculations of mass flow in each process stage of the case of waste glass treatment

	Process stage	**Calculations**
1	Collected waste glass	m_1
2	Sorted, recyclable glass cullet	$m_1 \times \eta_{sorting}$
3	Losses, scrap and fine stream	$m_1 \times (1 - \eta_{sorting})$
4	Sorting output flint cullet	$m_2 \times x_{Flint}$
5	Sorting output darker coloured cullet	$m_2 \times x_{Darker}$
6	Sorting output mixed cullet	$m_2 \times x_{Mixed}$

The considered system was formed based on information from a glass sorting plant in Italy and information found in the Ecoinvent database [26]. The input value of 300 000 000 kg was based on the yearly amount of sorted material in the previously described Eurovetro sorting plant. The sorting process and the transportation were modeled with the same processes from Ecoinvent as in the case of the glass bottle. The efficiency of the plant was assumed to be 85 % based on information received from Eurovetro. The ratio of the output products was based on the information given by Eurovetro with some modifications. The fine stream was not considered for recycling, and the white and half-white streams were considered as one output. The share of each output where therefore assumed to be:

$$X_{flint} = 0.16 \tag{3.30}$$

$$X_{Darker} = 0.42 \tag{3.31}$$

$$X_{Mixed} = 0.42 \tag{3.32}$$

The sample values were based on the information given by Eurovetro. No data were given for the colour composition of the dark and mixed stream. So, for the dark stream, the colour composition was assumed to be the same as in the case of the bottle. The mixed stream was then assumed to have the same colour compositions as if the flint stream and the darker stream were combined. A summary of the considered impurities and colour contamination in each output stream is presented in table 3.8

Table 3.8: Amount of impurities and colour contamination in the output streams

<table>
<tr><th>Impurities</th><th>Flint stream
(ppm)</th><th>Darker stream
(ppm)</th><th>Mixed stream
(ppm)</th></tr>
<tr><td>Fe metals</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Non-Fe metals</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Inorganics</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td>Organics</td><td>300</td><td>300</td><td>300</td></tr>
<tr><td>Lead</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td>Colour</td><td>(%)</td><td>(%)</td><td>(%)</td></tr>
<tr><td>Flint</td><td>99.5</td><td>15</td><td>38</td></tr>
<tr><td>Amber</td><td rowspan="2">0.5</td><td>5</td><td rowspan="2">62</td></tr>
<tr><td>Green</td><td>80</td></tr>
</table>

3.4.3.3 Impact

The impact of the system was analysed in the same way as in the case of the glass bottle. The avoided impact and the total impact for this case were calculated as follows:

$$I_{Avoided} = I_{Rawmaterial} \times m_{sub} - I_{Transportrecycling} \times m_2 \tag{3.33}$$

$$I_{Tot} = (I_{Transport,Sorting} + I_{Sorting}) \times m_1 - I_{Avoided} \tag{3.34}$$

3.4.3.4 Substituted Material

The substituted material was determined in the same way as in the case of the glass bottle, but in this case, the calculations were made for each of the considered output streams.

3.4.3.5 Substituted Amount of Material

The substituted amount of material was determined in the same way as in the case of the bottle. Also, here a base scenario was created with a one-to-one (1:1) substitution ratio to use in the comparison of the effect of the different scenarios.

Case 1 less tolerant substitution
For this scenario, any of the streams fulfills the criteria of any of the quality categories. Neither of the categories could therefore be targeted and the technical substitution coefficient was therefore set to 0 in all categories.

Case 2 more tolerant substitution
The flint stream was able to target categories A and B:2. The amount of material that was supposed to be in category B:1 was instead put into category A. The substituted amount of material by the flint stream was then calculated as follows:

$$m_4 = m_A + m_{B:1} + m_{B:2} \tag{3.35}$$

$$m_{B:1} = 0 \tag{3.36}$$

$$m_A = (MS_A + MS_{B:1}) \times m_4 \tag{3.37}$$

$$m_{B:2} = MS_{B:2} \times m_4 \tag{3.38}$$

$$m_{sub,A} = 1.17 \times S_{Technical,A} \times m_A \tag{3.39}$$

$$m_{sub,B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.40}$$

The darker colour stream was instead able to target category B:1 and B:2. The amounts that were supposed to be in category A were therefore put into category B:1. And the substituted amount of material by the darker stream was then calculated as:

$$m_5 = m_A + m_{B:1} + m_{B:2} \tag{3.41}$$

$$m_A = 0 \tag{3.42}$$

$$m_{B:1} = (MS_A + MS_{B:1}) \times m_5 \tag{3.43}$$

$$m_{B:2} = (MS_{B:2} \times m_5) \tag{3.44}$$

$$m_{sub,B:1} = 1.17 \times S_{Technical,B:1} \times m_{B:1} \tag{3.45}$$

$$m_{sub,B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.46}$$

The mixed colour stream could only target category B:2. The substituted amount of material by the mixed stream was therefore calculated as follows:

$$m_6 = m_A + m_{B:1} + m_{B:2} \tag{3.47}$$

$$m_A = m_{B:1} = 0 \tag{3.48}$$

$$m_{B:2} = (MS_A + MS_{B:1} + MS_{B:2}) \times m_6 \tag{3.49}$$

$$m_{sub:B:2} = 1.17 \times S_{Technical,B:2} \times m_{B:2} \tag{3.50}$$

The total amount of substituted material was then calculated by summarising all the substituted material in each stream.

$$m_{sub,tot} = \sum_{i=1}^{n} m_{sub,i} \tag{3.51}$$

4

Results and Discussion

This study aimed to introduce a model for how to deal with substitution and account for quality degradation between secondary material and raw material. The focus of the study has been on glass cullet as a secondary material and quality aspects in the substitution of raw materials in remelt applications. In this section, the results and findings of the study will be presented and discussed further.

4.1 Literature Review and Formed Model

4.1.1 Quality Categories and Application

As found in the literature review most of the substitution models takes their base in a secondary application of the material. It could also be seen in the information found that the replaced raw material depends on the secondary application and the quality requirements for that application. Therefore, also this model started by looking into the possible secondary applications. Some models tried to make a difference between applications requiring different quality levels of secondary material. In the article *Quality of recycling: Towards an operational definition* [14] there is presented a ranking of quality categories for different secondary materials. This model was therefore based on the secondary applications of the material and the ranking of them into different quality categories based on once presented in the article.

4.1.2 Substitutability Based on Technical Properties

Many of the substitution coefficients found in the literature review focus on the technical substitutability of the secondary material compared to the raw material. In the article *Quality model for recycled plastics (QMRP)* [20] it is presented a model for calculating the technical substitution for plastic taking into consideration different key characteristics of the raw material and how well the secondary material matches these characteristics for a certain application. This framework was chosen for calculating the technical quality substitutability, but it was instead calculated for each of the formed categories instead of for a single application. The major reason for this choice was that it considered several different characteristics for the considered application instead of just one.

4.1.3 Market Substitutability

The market substitutability has in some of the found models been evaluated as the potential share of the total market that the secondary material can target compared to the virgin raw material. The substituted material depends on both the market that can be targeted and the demand for the material. Therefore both these aspects must be evaluated. In this model, the market substitutability is therefore instead based on both these criteria.

Considered that the quality of the secondary material was high, and it fulfilled the requirement of all the categories and there was a high demand in all categories. Then, the market substantially constant would be one and all the material that was recycled would end up in a category replacing virgin material. If the quality output of the secondary material instead were low and not able to target some of the quality categories, it would not be able to substitute material in these categories. But, if the demand in the other categories were still high the material would then instead replace material in a lower-quality category. The market substitutability would therefore be one also in this case, because all of the recycled material has a functional demand. Instead, if the quality of the output material is low and the market for the lower-quality categories is saturated then the substitution would be limited by these markets' possibility to use the secondary material. The market substitutability would then be considered as in Eriksen et al. [21].

4.1.4 Consept of Model Formed

In the overall formed model, the substituted material is defined by considering both the technical quality of the secondary material and the applicability of the material. Quality categories based on different applications and their requirements were therefore formed. The quality of the secondary material determines what category it can target. In the case of several possible options, the division between the options is assumed to follow the market share of those options. However, in the case that the quality of the secondary material is not sufficient for some categories, that amount favors the higher-quality category of which it is suitable unless saturated. When the target categories are determined a quality coefficient for each of the applications can be calculated based on how well the secondary material performs in relation to raw material in that category. The quality substitutability coefficients are then used to evaluate the degree of substituted material in each category. The total avoided burden can then be evaluated as the total avoided impact from the avoided virgin material in each of the considered quality categories.

4.2 Developed Model for Substitution of Glass

Glass as a material is as previously mentioned often considered to be fully circular and assumed to be able to be recycled an endless number of times, but as has been mentioned in the study there are several factors that limit the functionality and applicability of the glass cullet as a secondary material. The quality of glass cullet can therefore decrease compared to raw materials, and a one-to-one (1:1) substitution would be an overestimation.

Because of glass being an inert material and its characteristics does not deteriorate, most of its quality degradation aspects is related to the secondary material being less pure. These impurities can then cause problems in the production of new glass products. This is an aspect that make glass a bit special compared to other secondary materials. The quality aspects are therefore not really the quality of the glass cullet itself but rather the purity of the sample and the efficiency of the sorting process.

The developed model for the substitution of glass consists of quality categories with different quality requirements. The quality degradation in the model is evaluated based on two key quality criteria divided into subcategories. For each quality category, the assigned technical and market quality specifications as well as the market shares are presented. The technical quality specifications are presented as two extreme cases. Case 1 represents a case with stricter quality requirements and a lower tolerance while Case 2 represents a case with lower-quality requirements and a higher tolerance.

4.2.1 Developed Quality Categories

Three different quality categories were formed based on different secondary remelt applications for recycled container glass cullet. The formed categories were category A, which is based on the applicability in flint container glass, category B:1 which instead is based on the applicability in darker coloured container glass, and B:2 which is based on the applicability in insulation material.

4.2.1.1 Category A Container Glass, Flint

In category A the material is replacing virgin glass material of the same material application as the previous product. It replaces material for container glass of the same colour as before. The material is thereby in the same quality category as virgin material, and it is possible to recycle it several times. If we start with flint container glass, the application for category A is flint container glass.

Market quality: There is a high demand for the material in this category and the secondary market is functioning. There are no further restrictions limiting the use of secondary material of this quality in the production of glass.

Market share: The market share is then the same as for the initial application which is flint container glass, the market share for category A is then:

$MS_A = 29.75\,\%$

Technical quality: Even though it fits into the requirements for the initial application it may still have gone through some quality degradation in form of contamination and colour. The technical quality substitutability is therefore determined based on the technical quality requirements of this category.

Accepted intervals: The intervals of this category represent the quality requirements for flint container glass. The intervals, ideal value, and weighting of the two extreme cases are presented in tables 4.1 - 4.4.

Table 4.1: Accepted intervals, ideal value, and weighting for impurities for category A in Case 1

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	(0-2)	0	0.1
Non-Fe	(0-3)	0	0.1
Inorganic	(0-20)	0	0.1
Organic	(0-300)	0	0.1
Heavy metals	(0-200)	0	0.1

Table 4.2: Accepted intervals, ideal value, and weighting for colour for category A in Case 1

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-1)	0	0.5

Table 4.3: Accepted intervals, ideal value, and weighting for impurities for category A in Case 2

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	(0-50)	0	0.1
Non-Fe	(0-60)	0	0.1
Inorganic	(0-100)	0	0.1
Organic	(0-2000)	0	0.1
Heavy metals	(0-200)	0	0.1

Table 4.4: Accepted intervals, ideal value, and weighting for colour for category A in Case 2

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-6)	0	0.5

4.2.1.2 Category B:1 Container Glass, Darker Colour

The cullet still fits the requirement to be recycled to container glass but is of a darker colour than the initial application. The quality has therefore decreased because of colour contamination but it still fits into the other impurity requirements for container glass. The darker colour causes a limitation in its application potential. The product is still able to be recyclable several times. If the initial application was flint container glass, then this category includes coloured container glass.

Market quality: There is a high demand for the material in this category and the secondary market is functioning. There are no further restrictions limiting the use of secondary material of this quality in the production of glass.

Market share: The cullet in this category has the total market share for container glass apart from the market share of non-coloured glass.

$MS_{B:1} = 55.25\,\%$

Technical quality: The technical quality in terms of colour has decreased and maybe also in terms of the overall contaminants but not so much that it can no longer be used in the production of container glass. The technical quality substitutability is therefore determined based on the technical quality requirements of this category.

Accepted intervals: The intervals of this category represent the quality requirements for coloured container glass. The accepted values for impurities are the same but the colour limitations vary between the colours. The intervals, ideal value, and weighting of the two extreme cases are presented in tables 4.5 - 4.10.

Table 4.5: Accepted intervals, ideal value, and weighting for impurities for category B:1 in Case 1

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	(0-2)	0	0.1
Non-Fe	(0-3)	0	0.1
Inorganic	(0-20)	0	0.1
Organic	(0-300)	0	0.1
Heavy metals	(0-200)	0	0.1

Table 4.6: Accepted intervals, ideal value, and weighting for colour for category B:1 in Case 1, based on amber glass

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-10)	0	0.5

Table 4.7: Accepted intervals, ideal value, and weighting for colour for category B:1 in Case 1, based on green glass

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-10)	0	0.5

Table 4.8: Accepted intervals, ideal value, and weighting for impurities for category B:1 in Case 2

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	(0-50)	0	0.1
Non-Fe	(0-60)	0	0.1
Inorganic	(0-100)	0	0.1
Organic	(0-2000)	0	0.1
Heavy metals	(0-200)	0	0.1

Table 4.9: Accepted intervals, ideal value, and weighting for colour for category B:1 in Case 2, based on amber glass

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-20)	0	0.5

Table 4.10: Accepted intervals, ideal value, and weighting for colour for category B:1 in Case 2, based on green glass

Colour	**Interval** $I_{min} - I_{max}$ **(%)**	I_{ideal} **(%)**	j_i
Other colours	(0-30)	0	0.5

4.2.1.3 Category B:2 Insulation Material

The cullet that fits into this category fits into the criteria to be recycled to insulation wool. Insulation wool has other criteria for impurities than what container glass has. It also doesn't have as strict requirements on colour contamination. Some of the cullet that is suitable for insulation wool may also be suitable for container glass production.

Market quality: There is a high demand for the material in this category and the secondary market is functioning. There are no further restrictions limiting the use of secondary material of this quality in the production of glass.

Market share: The cullet is suitable for the market share of insulation wool and some parts of the cullet may also be suitable for the market of container glass of different colours.

$MS_{B:2} = 15\,\%$

Technical quality: The technical quality substitutability is determined based on the technical quality requirements of this category which are based on the requirements for insulation wool. The technical quality in terms of colour has decreased and maybe also in terms of the overall contaminants, it may have decreased so it can no longer be used in the production of container glass.

Accepted intervals: The intervals of this category represent the quality requirements for insulation wool. The intervals, ideal value, and weighting of the two cases are presented in table 4.11 and 4.12.

Table 4.11: Accepted intervals, ideal value, and weighting for impurities for category B:2 in Case 1

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	5	0	0.5
Non-Fe			
Inorganic	0-20	0	0.25
Organic	0-500	0	0.25

Table 4.12: Accepted intervals, ideal value, and weighting for impurities for category B:2 in Case 2

Impurities	**Interval** $I_{min} - I_{max}$ **(ppm)**	I_{ideal} **(ppm)**	j_i
Fe	0-50	0	0.25
Non-Fe	0-60	0	0.25
Inorganic	0-100	0	0.25
Organic	0-3000	0	0.25

4.3 Case Study

When the case studies were developed, many assumptions were made to create a general case representing European conditions where the effect of using the model could be shown. The results of the case studies themself are therefore rather uncertain, but they show the use of the model. The results from the cases should therefore rather be considered as the change in comparison between the cases than as a final impact of the system. However, the aim of the implementation in the case studies was to show the applicability of the model rather than to determine the exact impact of the system.

4.3.1 Case, Life Cycle of a Glass Bottle

4.3.1.1 Material Flow Analysis

The result of the material flow analysis is shown in table 4.13. The tabular show the mass flow for container glass per functional unit in each process stage of the case study. For each 0.45 kg of glass or for each glass bottle produced, results in 0.316 kg glass cullet that is available for recycling after the sorting step. Material losses occur both during the use phase of the bottle and during the sorting and treatment process of the cullet.

Table 4.13: Calculated mass for each process stage in the case of the bottle

	Process stage	Mass (kg)
1	Produced flint container glass	0.450
2	Container glass collected for recycling	0.342
3	Container glass sent to landfill	0.108
4	Sorted cullet available for recycling	0.316

4.3.1.2 Technical Quality Substitution Coefficients

The calculated quality substitution coefficients for each of the quality categories for the two cases are presented in table 4.14. The overall stricter requirements in Case 1 resulted in all the material being substituted in Category B:2 which still had a lower substitution ratio than for both the targeted categories in Case 2 where the restrictions were less strict. For case 2 the substitution coefficient was much higher in category B:2 because of the lower-quality requirements. The quality requirement between the categories is relatively similar between the categories in terms of contaminants, but in category B:2 also the colour contamination is given equal importance as the contaminants. This results in the substitution coefficient of category B:1 being affected by the colour contamination in the sample, which limits its functionality as a replacement for virgin material in the application of container glass.

Table 4.14: Calculated quality substitution coefficients for each of the quality categories in Case 1 and Case 2 of the bottle

Quality category	Quality coefficient Case 1	Quality coefficient Case 2
A: Flint container glass	0	0
B:1 Darker container glass	0	0.745
B:2 Insulation wool	0.685	0.931

4.3.1.3 Substituted Material

The amount of substituted material in each category for the three scenarios is presented in table 4.15. The total amount of substituted material and the percentual decrease in the different scenarios is presented in figure 4.1 and 4.2. As can be seen, most material were substituted in the base scenario with the one-to-one (1:1) substitution coefficient. Instead in Case 1 with the lower tolerance interval, the lowest total amount of material was substituted. In Case 2 more material was substituted in category B:1 than in category B:2 because of the division based on market share even though the substitution coefficient was much higher in category B:2 because of the lower-quality requirements.

Table 4.15: Substituted amount of material in the case of the bottle in each of the considered scenarios

Scenario	Category A (kg)	Category B:1 (kg)	Category B:2 (kg)	Total substituted material (kg)	%
1:1 substitution	-	-	-	0.370	100
Case 1	-	-	0.254	0.254	68.5
Case 2	-	0.234	0.052	0.286	77.3

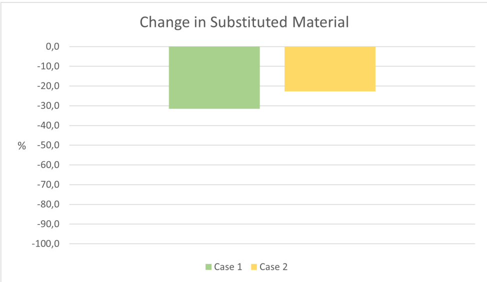

Figure 4.1: Percentual change in substituted amount of material compared to the base scenario

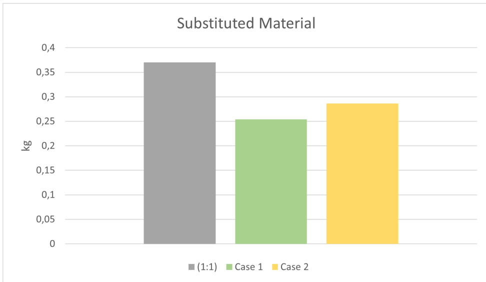

Figure 4.2: Total amount of substituted material

In the case of the bottle also a saturated scenario was presented to show the effect if the lower-quality categories were saturated. As it is now, this is an unrealistic assumption based on that the secondary market of glass is functioning and there is a market for the considered quality categories. This can however become more relevant when more and more material is recycled, and also lower-quality categories are included. If a large fraction of the used material is recycled and the quality of the secondary material does not fulfill the requirements to target the high-quality categories there is a risk that the market of the lower-quality categories gets saturated. The amount of material that can be substituted could then be limited by the amount of material that can be taken up by the categories that the secondary material can target. As it is now the categories considered in this study do not really cover all the secondary market for glass cullet. In order for this to be more functional the categories need to cover a broader range of applications to better mirror the secondary market.

The amount of substituted material in each category under saturated conditions is presented in table 4.16. The total amount of substituted material and the decrease in percentage in the different scenarios is presented in figure 4.3 and 4.4 As can be seen in the tabular, the same categories are targeted as in the non-saturated case but the substituted amount of material is less. This is because the categories were considered saturated and therefore only could be targeted by the amount of material represented by their market share. This had a big effect on the total substituted material, especially in Case 1 where only category B:2 could be targeted which had a relatively small market share.

Table 4.16: Substituted amount of material in the case of the bottle in each of the considered scenarios, when the market where assumed to be saturated

Scenario	Category A (kg)	Category B:1 (kg)	Category B:2 (kg)	Total substituted material (kg)	%
1:1 substitution	-	-	-	0.370	100
Case 1	-	-	0.038	0.038	10.3
Case 2	-	0.152	0.052	0.204	55.1

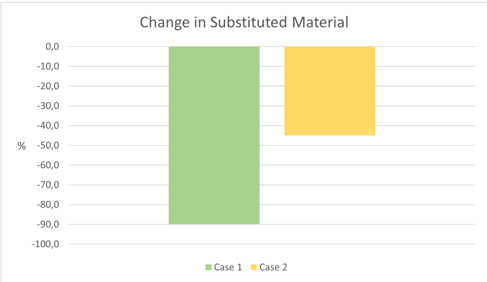

Figure 4.3: Percentual change in substituted amount of material compared to the base scenario, saturated conditions

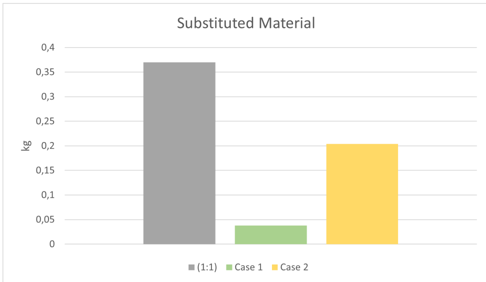

Figure 4.4: Total amount of substituted material, saturated conditions

4.3.1.4 Avoided Impact

The avoided impact from the substituted material in each of the scenarios of the bottle is presented in figure 4.5 and 4.6 below. As can be seen in the figures the implementation of the substitution model had a big effect on the relative avoided impact.

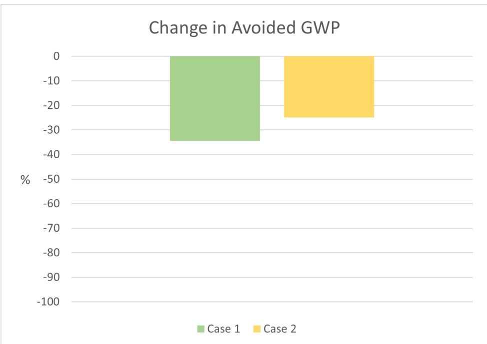

Figure 4.5: Percentual change in avoided Global Warming Potential compared to the base scenario

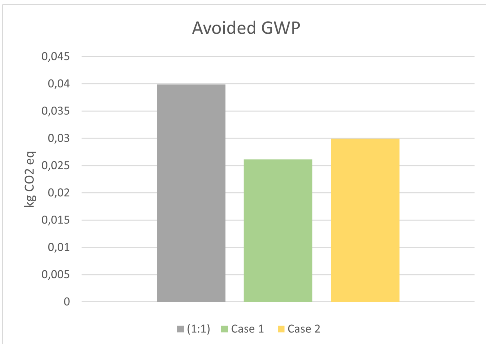

Figure 4.6: Avoided Global Warming Potential

The avoided impact from the substituted material in each of the scenarios of the saturated case is presented in figure 4.7 and 4.8 below. As can be seen, almost no impact was avoided in case 1 because of the low substitution ratio, and a much lower amount of impact was substituted for case 2 than under normal conditions.

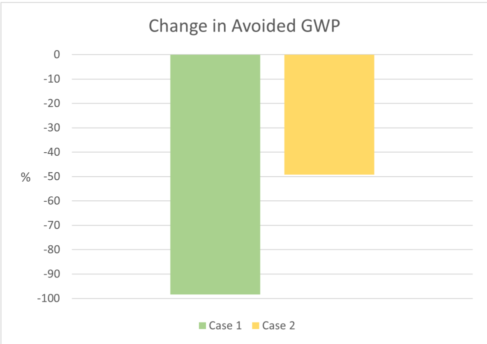

Figure 4.7: Percentual change in avoided Global Warming Potential compared to the base scenario, saturated conditions

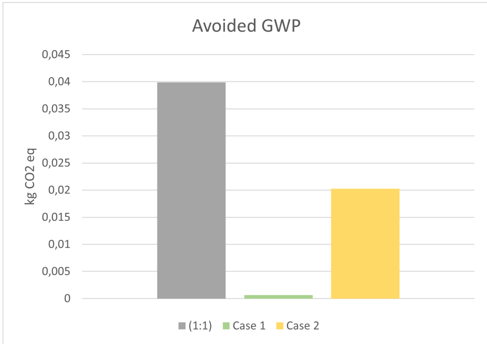

Figure 4.8: Avoided Global Warming Potential, saturated conditions

4.3.1.5 Total Impact

The total impact of the system of the bottle is presented in figure 4.9 and 4.10 below. As can be seen in the figures the implementation of the models had an effect on the total impact but since the overall impact of the system is so big the relative effect on the total system is relatively small.

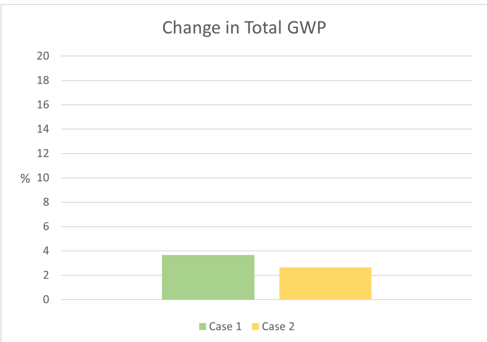

Figure 4.9: Percentual change in total Global Warming Potential compared to the base scenario

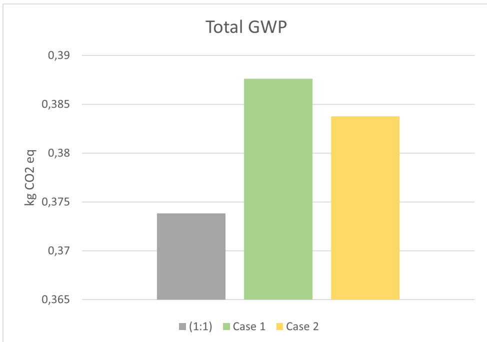

Figure 4.10: Total Global Warming Potential

The total impact of the system under saturated conditions is presented in figure 4.11 and 4.12 below. In the same way, as discussed before, the implementation has an effect on the total impact of the system but because the overall impact of the system is so much bigger the relative effect is relatively small. Even for Case 1 where a very little amount of material was substituted the increase in total impact was only around 10 %.

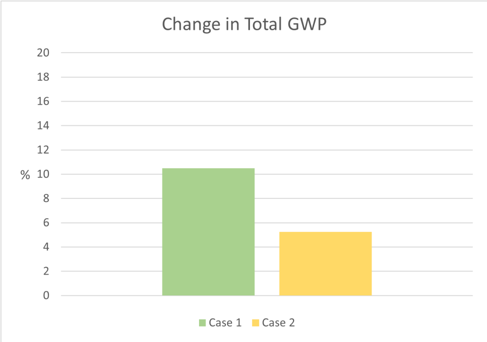

Figure 4.11: Percentual change in total Global Warming Potential compared to the base scenario, saturated conditions

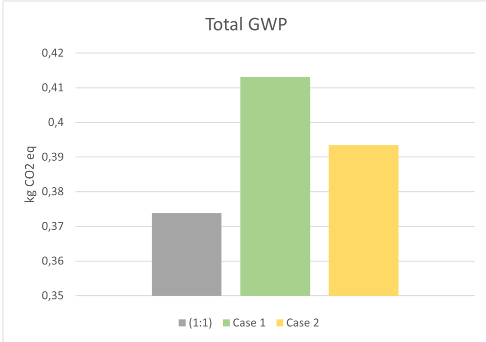

Figure 4.12: Total Global Warming potential, saturated conditions

As can be seen in the results of the case study of the bottle the implementation of the model had a big effect on the amount of virgin material that was substituted in the two cases and the avoided impact in comparison to the base scenario. However, the change in the total impact of the system was not that big because of the much bigger impact of the total system, mainly from the initial production of the bottle.

4.3.2 Case, Treatment of Waste Glass

4.3.2.1 Material Flow Analysis

The results of the material flow analysis of the case regarding the treatment of waste glass are shown in table 4.17. In the tabular, the mass flow is shown per functional unit for every process stage. The input of 300 000 000 kg of collected waste glass results in the output of 44 400 000 kg of flint cullet, 116 550 000 kg of darker coloured cullet and 116 550 000 kg of mixed cullet.

Table 4.17: Calculated mass for each process stage in the case of treatment of waste glass

	Process stage	Mass (kg)
1	Collected waste glass	300 000 000
2	Sorted, recyclable glass cullet	277 500 000
3	Losses, scrap and fine stream	22 500 000
4	Sorting output flint cullet	44 400 000
5	Sorting output darker coloured cullet	116 550 000
6	Sorting output mixed cullet	116 550 000

4.3.2.2 Technical Quality Substitution Coefficients

In table 4.18-4.20 the calculated quality substitution coefficients for each output stream are presented. The flint stream could not target any of the categories for Case 1, resulting in all the substitution coefficients being 0. For Case 2 the stream could target both categories A and B:2. Category B:1 could not be targeted resulting in the substitution coefficient being 0 for that category.

Table 4.18: Calculated quality substitution coefficients of the flint stream for each of the quality categories in Case 1 and Case 2 of the waste glass treatment

Quality category	Quality coefficient Case 1	Quality coefficient Case 2
A: Flint container glass	0	0.906
B:1 Darker container glass	0	0
B:2 Insulation wool	0	0.884

The darker stream was not able to target any of the quality categories for Case 1. Instead for Case 2, the stream was able to target both category B:1 and category B:2, but not category A.

Table 4.19: Calculated quality substitution coefficients of the darker stream for each of the quality categories in Case 1 and Case 2 of the waste glass treatment

Quality category	Quality coefficient Case 1	Quality coefficient Case 2
A: Flint container glass	0	0
B:1 Darker container glass	0	0.730
B:2 Insulation wool	0	0.884

The mixed stream could not target any category for Case 1 and could only target category B:2 for Case 2. The substitution coefficient was therefore 0 for all categories in Case 1 and for categories A and B:1 in Case 2.

Table 4.20: Calculated quality substitution coefficients of the mixed stream for each of the quality categories in Case 1 and Case 2 of the waste glass treatment

Quality category	Quality coefficient Case 1	Quality coefficient Case 2
A: Flint container glass	0	0
B:1 Darker container glass	0	0
B:2 Insulation wool	0	0.884

4.3.2.3 Substituted Material

The amount of substituted material in each of the scenarios for each category is presented in table 4.21. And the total amount of substituted material and the decrease in the percentage of substituted material is presented in figure 4.13 and 4.14 As can be seen in the tabular, in Case 1 no material was substituted because the streams did not fulfill the stricter requirements of Case 1. As previously mentioned in the case of the bottle, this indicates that the intervals of Case 1 may be too strict, since the output streams of the sorting plant were targeting remelt applications according to the sorting plant. Instead, in Case 2 with higher tolerance, the material was substituted in all the categories. Approximately 83.2 % of the amount substituted in the base scenario was substituted in Case 2.

Table 4.21: Substituted amount of material in the case of treatment of waste glass for each of the considered scenarios

Scenario	Category A (kg)	Category B:1 (kg)	Category B:2 (kg)	Total substituted material (kg)	%
1:1 substitution	-	-	-	324 675 000	100
Case 1	0	0	0	0	0
Case 2	40 004 745	84 663 749	145 493 113	270 161 607	83.2

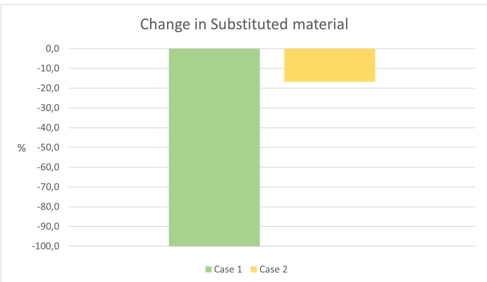

Figure 4.13: Percentual change in substituted amount of material compared to the base scenario

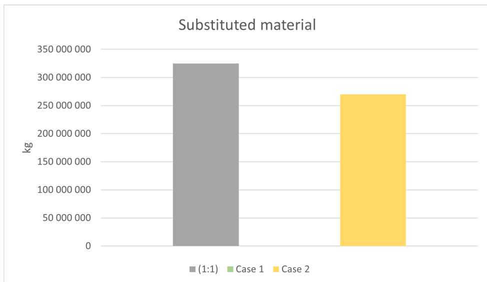

Figure 4.14: Total amount of substituted material

4.3.2.4 Avoided Impact

The avoided impact from the substituted material in each of the scenarios is presented in figure 4.15 and 4.16 below. For Case 1 no material could be substituted and therefore no avoided impact could be accounted for. Instead for Case 2, some material was substituted and some avoided impact could be accounted for.

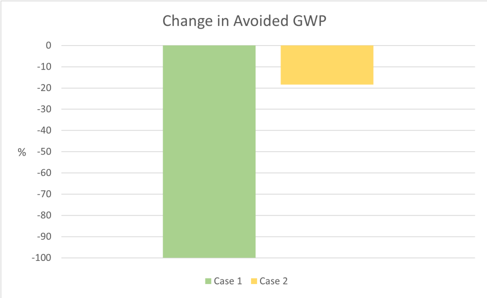

Figure 4.15: Percentual change in avoided Global Warming Potential compared to the base scenario

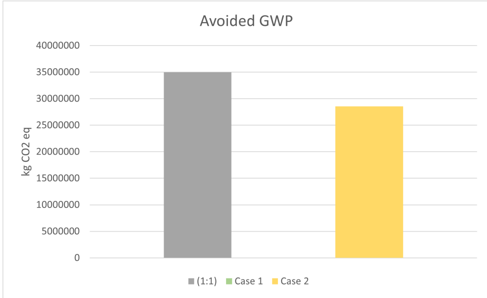

Figure 4.16: Avoided Global Warming Potential

4.3.2.5 Total Impact

The total impact of the system as well as the percentual difference between the two scenarios in regard to the base scenario is presented in figure 4.15 and 4.16 below. Since no material could be substituted for Case 1 because of the strict quality requirements no avoided impact were accounted for which resulted in a positive total impact of the waste treatment process. Instead, for Case 2 where the material could target some categories the quality substitution coefficient here had greater importance also in the evaluation of the total impact than in the case of the bottle. Taking quality degradation into consideration can therefore be of importance when evaluating and comparing the impact of different waste treatment systems.

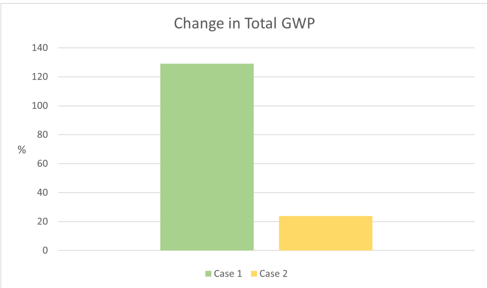

Figure 4.17: Percentual change in total Global Warming Potential compared to the base scenario

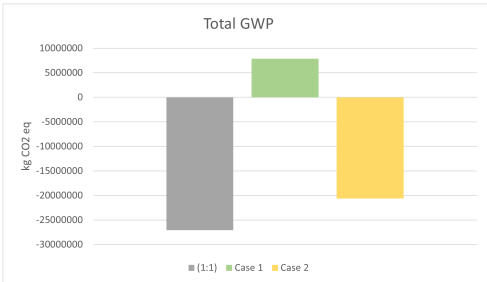

Figure 4.18: Total Global Warming potential

4.4 Evaluation of the Model

The developed model for the substitutability of glass includes several assumptions, limitations, and simplifications which on one hand make the model less in line with reality but on the other hand make it easier to apply. The model is in this study limited to only three categories considering three secondary applications and the requirements for those. There are many other secondary applications for glass and for the model to be more representative of reality it would need to include more categories and applications. It is also limited to only remelt applications, replacing raw material for virgin glass. But in reality, some of the glass cullet is used in non-remelt applications, replacing other materials. The model should therefore be expanded to also include non-remelt applications and the substitution of other materials.

4.4.1 Quality Factors and Weighting

The considered quality factors in the categories are also simplification, in reality, there are also other aspects determining the quality of the secondary material and including them could give a better picture of the quality. But it would also require more information and make the model more complicated. In the calculation of the quality coefficient, the weighting between the different properties has an important impact. It is therefore important to have a correct weighting of the importance between the different properties to have a fair evaluation of the quality degradation of the sample in relation to a certain application. In this study, the properties were equally weighted, but a more informed weighting could give a more correct coefficient, but also this would require a lot more information to be collected and evaluated.

Another limitation of the model is that it only considers the quality degradation in regard to each category and is not based on the overall quality degradation in that sense. The division between the categories will therefore have an impact on the amount of substituted material. A lower category will have less strict requirements resulting in a larger amount of material will be recycled if these categories are targeted rather than the higher-quality aspects. It therefore appears like it would be beneficial to have a higher fraction of low-quality cullet. This effect can be seen in both case studies. But also because of the weighting in this study more relative importance is given to each of the impurities in category B:2 than in category A and B:1 cause category B:2 is not considering colours, even though these factors might have a similar importance for all the considered categories. The effect of this could be seen in the flint stream in the case of the waste glass treatment.

4.4.2 Accepted Intervals

The determination of the quality substitution coefficients is highly dependent on the selected interval of limitations. However, there is no clear answer for what the accepted interval for different applications is, it varies depending on the country, organisation, and company asked. In this study therefore two extreme cases were created from the data collected, but more data should be collected for a better image of the actual limiting intervals. Case 1 which had more restrictive limitation intervals was mostly based on specific company information while Case 2 instead to a large extent was based on values from the end of waste criteria for glass cullet. Case 1 is therefore probably way too limiting and does not reflect the overall market acceptability, which also can be seen in the results from the case study regarding the waste glass treatment. According to the sorting plant, all the products with these specifications had a secondary market, instead for Case 1 the output streams did not fulfill any of the criteria for the quality categories. Case 2 is probably way too accepting hence it is the end of waste criteria for glass cullet in general, not only considering remelt applications. The real acceptable interval probably lies somewhere in between, as also can be seen in the information given from the sorting plant about the industrial specifics for the Italian industry presented in Appendix I. The industry acceptance values are here somewhere in between the two cases, and the samples from the sorting plant fulfill the requirements of these criteria.

4.4.3 Improvements and Future Work

To evaluate the impact of recycling it is important to determine the quality degradation in materials and the substitutability between materials. In order to do so, more quality coefficients and substitution models need to be developed dealing with a broader range of materials. There is room for improving the quantification of the quality degradation and the substitutability. Not only by including more materials but also by improving already existing models for materials. The model for the substitution of glass presented in this study could as previously mentioned be further improved by including more quality categories and more secondary applications for glass such as non-remelt applications. The categories could also be further developed and specified by including more quality factors and improving the weighting and the intervals of the factors to better represent real requirements.

5
Conclusion

This study has described a current issue in LCA on how to determine the substitutability of recycled secondary materials. The existing models are few and focus on different approaches. Also, the covered secondary materials are limited, often focusing on plastic. Glass on the other hand is often seen as a fully circular material, even though several quality aspects are affected when recycled. Few studies consider the quality degradation in glass from recycling. An evaluation of the substitution of glass is of importance for a proper evaluation of the environmental impact of glass recycling and for the movement towards a circular economy.

The possibility of replacing virgin material depends on the quality of the glass cullet and the requirements of the application. The study has noted that there are several different aspects that need to be considered for the cullet to be applicable, and not only one aspect can be taken into consideration. This study has therefore presented a model for how to determine the substitutability of glass cullet based on its functionality and applicability. The study is therefore progress in the way of quantifying the substitutability of secondary material.

The approach was implemented in two case studies where the substitutability coefficient was calculated for some cullet samples in relation to three quality categories. The conclusions given from the case studies were that accounting for quality degradation could have an important effect on the results of the study and the total impact, especially when evaluating waste treatment systems. A proper quantification of the substitutability between the glass cullet and the replaced material is therefore important to correctly evaluate the environmental impact of the studied system.

Another conclusion from the study is that glass is a material that is already recycled to a large extent and the secondary market is now functioning well. But when a large amount of material is recycled the quality of the secondary material is important for the secondary material to be able to replace material in high-quality applications with stricter requirements. Otherwise, there is a risk that the market for low-quality applications gets saturated which will affect the amount of material that can be substituted which could be seen in the case study.

The calculation of the substitutability could be further developed by considering more quality properties such as physicochemical type and improving the weighting of the properties depending on their relative importance. Other studies can be made following the concepts but expanding the model with other quality categories and other requirements or substituting other materials. A further developed system of calculating the substitutability of secondary material would lead to more accurate and correct conclusions when assessing the impact regarding recycling activities than assuming a one-to-one (1:1) replacement and would enable better informed advices and decisions.

It is hard to quantify substitutability and quality degradation in a correct and proper way. The quality of a material depends on many different aspects and differs depending on the situation and what application it targets. Because the concept of quality is vaguely defined and substitutability is very situation dependent the developed model is going to be an oversimplification of reality. However, by taking these aspects into consideration the quantification is trying to come closer to reality than by not considering these aspects at all. Waste treatment processes deal with many different materials and to properly evaluate these processes in LCA there is a need for a broad field of substitution coefficients adapted for all these secondary materials. The majority of the available substitution coefficients and models are adapted to plastic, so there are many materials still to be covered and included.

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