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Comparative Life Cycle Assessment (LCA) of the Roadside Noise barriers

Master's thesis in Design and Construction Project Management

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ABSTRACT

The transport sector has a significant contribution to the global warming potential and road infrastructure is accounted for up to 40 percent of it. Therefore, there is a growing interest among policymakers in investigating sustainable development in these areas. Among road infrastructure, this thesis chooses noise barriers to conduct a comparative life cycle assessment (LCA). The LCA methodology follows ISO 14040 standard, consisting of goal and scope definitions, inventory analysis, impact assessment, and interpretation. Ecoinvent 3.8 is used as a database and environmental impact is assessed through OpenLCA 1.11.0. Besides comparing the results of various noise barriers, this project also aims to compare the difference between two end-of-life scenarios. In one scenario, all material will be disposed of at the end of life while in the second one, the recyclable amount of each material will be treated to be used in the latter cycles. The results indicate that raw materials processing has the highest impact in the whole life cycle of barriers. Therefore, decreasing primary raw materials consumption can contribute significantly to diminishing environmental impacts. Additionally, the findings through dominance analysis and discussion can be helpful for decision-makers to detect the potential areas to improve.

Key words: Life cycle assessment (LCA), Roadside noise barriers, Environmental impact, Global warming potential, Circular transition.

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Preface

This thesis was carried out at the department of Architecture and Civil Engineering at the Chalmers University of Technology. It was conducted from January 2023 to May 2023 as the master's thesis encompassed 30 higher education credits for the program "Design and Construction Project Management".

I would like to express my deepest gratitude to my Supervisor and Examiner, Holger Wallbaum, Professor in sustainable building at the Chalmers University of Technology and PROCEEDR project coordinator, for his invaluable insights, constructive feedback, and great commitment throughout the whole process. I also want to extend thank you to my other supervisor, Anna Wöhler, Ph.D. candidate at the Chalmers University of Technology, for her contribution and feedback through the life cycle inventory modelling process.

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Finally, I would like to express my gratitude to all individuals who contributed to this project or supported me, especially my family whose great support, motivated me to continue and overcome challenges.

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Abbreviations

EIA	Environmental Impact Assessment
EPD	Environmental Product Declaration
FDP	Fossil Depletion Potential
FEP	Freshwater Eutrophication Potential
GHG	Greenhouse Gases
GWP	Global Warming Potential
HTP	Human Toxicity Potential
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MCDM	Multi-Criteria Decision Making
MEP	Marine Eutrophication Potential
NRA	National Roads Authority
NRD	Noise Reduction Devices
ODP	Ozone Depletion Potential
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
PROCEEDR	Optimising Resource Use for Roadside Infrastructure
QUIESST	Quietening the Environment for a Sustainable Surface Transport
SEA	Strategic Environmental Assessment
SLCA	Social Life Cycle Assessment
SM	Steel supporting structure + Metal panels
SP	Steel supporting structure + Plastic panels
ST	Steel supporting structure + Transparent panels
TAP	Terrestrial Acidification Potential
WDP	Water Depletion Potential

1 Introduction

The transport sector contributes to 24% of green gas emissions and road transport is accounted for 74% of it (Liljenström et al., 2020). Based on the traffic volume, surface type, and maintenance activities, road infrastructure could be accounted for 10 to 40 percent of road transport emissions (ibid). Therefore, there is a growing interest among the transport sector policymakers to use life cycle assessment (LCA) as a tool to support decisions regarding diminishing climate impacts of road infrastructure.

Optimizing resource use for roadside infrastructure (PROCEEDR) is a research project, coordinated by Chalmers University of Technology and consists of partners from three European countries and the United Kingdom and is financed by European National Road Authorities (NRAs) (PROCEEDR, 2023). PROCEEDR aims to create a software tool that assists NRAs in finding innovative and sustainable solutions which are facilitating linear to circular transition in the roadside infrastructure. The evaluation of these solutions is based on the environmental life cycle approach considering cradle-to-cradle impacts and a lean life cycle cost assessment (LCCA). Among roadside infrastructure, safety, and noise barriers are the most relevant ones which have been the focus of the research.

This master thesis aims to do a comparative life cycle assessment of the roadside noise barriers; however, the outcome of this work is not the tool that NRAs are looking for, but it is aiming to provide an overview of the related environmental factors and challenges which can help the PROCEEDR tool development. Therefore, this research is just focusing on the environmental impacts of the several selected noise barriers while safety barriers and life cycle cost assessment have not been considered. To summarise, the research questions are:

- What are the environmental impacts of noise barriers during the whole life cycle?
- How would the results change if closed-loop recycling will be considered?
- What are the modules/activities with dominant environmental impacts in each case?

The overall impact assessment will be done based on several environmental indicators; however, the dominance analysis will be conducted based on global warming potential, which is the main interest of the stakeholders.

This master's thesis starts with a background review of the related studies or projects. It will continue by describing the methodology based on ISO 14040 Environmental Life Cycle Assessment and presenting and interpreting the results, then will end by discussing the assumptions and factors that can affect the results.

2 Background

The background reviews are divided into two main parts. The first part is about infrastructure-related LCA studies and tools. This part is one of the primary reviews for developing the PROCEEDR tool. The second part is about roadside noise barriers and their sustainability-related studies, which is indicating the LCA's importance in this field and assisting the current thesis in choosing roadside noise barriers and conducting a lifecycle assessment.

2.1 LCA studies and tools in transportation infrastructure

Based on the Swedish Transport Administration's estimation, the construction of planned infrastructure will generate about 3.8 Mton green gas emissions during 2014-2025 which is 6% of the annual Swedish greenhouse gas (GHG) emissions (Miliutenko et al., 2014). The environmental impact of transport systems is usually associated with the traffic flow. However, the impact of construction, operation, maintenance, and demolition of the road infrastructure is not neglectable (ibid).

Guerrieri et al., (2015) did a comparative life cycle assessment of the road safety barriers, pavement, and traffic flow, based on four impact categories, Global warming potential (GWP), Photochemical ozone creation potential (POCP), acidification potential (AP), and Eutrophication potential (EP). The traffic flow showed the greatest environmental impact, however, the comparison between the road barrier and pavement showed an interesting output. The results of these two were comparable in three different categories (GWP, POCP, and AP) but the EP impact of safety barriers was three times more than the pavement. Therefore, to have a realistic view of road infrastructure's environmental potential, roadside barriers play an important role.

European Union requires two Environmental Assessment processes, Strategic environmental assessment (SEA) and Environmental Impact Assessment (EIA), to make sure that all environmental implication has been considered before a decision about road infrastructure is made (Miliutenko et al., 2014). EA provides a procedure for making decisions, while LCA is an analytical tool that provides information to support this process. Miliutenko et al. (2014) suggested based on the experience of four European countries (Sweden, Norway, Denmark, and Netherlands), that Life cycle consideration can be integrated into infrastructure planning in three ways, at the early stage of planning (as a separate process), integrated with EIA procedure/document or as a part of Cost-Benefit Analysis.

Early environmental assessment provides decision-makers with useful information in road construction projects (Lemperos & Potting, 2015). The aim of LCA tools is to assist the designer or environmental engineer in having an environmental assessment of the project. As a result, LCA tools have been constructed and developed in a way to provide the intended outcomes for its users (ibid). Therefore, there are different tools to assess infrastructures' environmental impacts, among which four of the most common ones in the North and central parts of Europe have been chosen for further investigation.

2.1.1 Klimatkalkyl

Klimatkalkyl (Climate Calculator) is a LCA tool that is developed by Trafikverket (the Swedish transport administration) to measure energy use and emissions associated with an infrastructure project during construction, operation, and maintenance (Reeves et al., 2020). This model was initially developed by WSP consultancy and funded by Trafikverket (Lemperos & Potting, 2015). It can be used both in planning and procurement processes by either the national road authority to set a baseline or by suppliers to select a less carbon emission design for the tender (Reeves et al., 2020).

Klimatkalkyl launched in 2013. First, as an Excel-based tool, it is now available as an online web-based tool. The tool resource is mostly based on previous construction calculations, environmental product declaration (EPD), or experienced-based data from the designer (Trafikverket, 2023), and it has been updated regularly in each version. It is explicitly developed for road and railroads project in Sweden and is conducted by the Swedish road administration. Therefore, it has specific predefined sections and elements which follow the Swedish procedures based on regulations and makes it difficult to be used outside of Sweden (Lemperos & Potting, 2015).

This tool has been developed based on the Swedish climate policy framework, TDOK 2015:0007, containing that Sweden should be CO₂ neutral by 2045 (Trafikverket, 2023). Therefore, the Swedish Transport Administration has set some regulations for using Klimatkalkyl. In April 2015, it has been mandatory to use Klimatkalkyl for calculating GHG emissions for the infrastructure projects that cost over 50 million SEK and are going to be finished after 2020. Since February 2016, it has also been used to meet the procurement requirements criteria. After March 2018, there are also requirements on both materials and fuels in maintenance and projects under 50 million SEK projects (Reeves et al., 2020).

Based on Reeves et al. (2020) if the supplier is using a material that is not in the tool's database, it should be approved by a third-party EPD auditor. Suppliers should submit tenders including carbon reduction measurements that have been calculated using Klimatkalkyl, the calculation is not needed to be included but during contract discussion, both parties will make sure that the carbon reduction goal will be achieved and at the end of the project climate declaration will be submitted based on the quantity of the actual material usage.

Klimatkalkyl also gives users the ability to compare different route options (for example tunnels and bridges) based on their associated GHG emissions (Reeves et al., 2020). After choosing the route, they can also measure energy consumption and GHG emissions to detect how they can make improvements and reduce emissions.

The user does not need to have an environmental engineering background (Lemperos & Potting, 2015) and has the flexibility to choose input. GHG emissions can be calculated based on input A: a specific activity of the project, e.g., a square meter of a bridge, or kilometer tunnel; Input B: more detailed information about material, component, or energy usage of the project, e.g., cubic meters of concrete per square meter of the bridge; or Input C: the combination of the last two options (Trafikverket, 2023). From version 5.0, there is an additional input (D) for road maintenance climate calculation. By altering the number of building components (for input A) or adjusting the materials and work steps included (for input B), users can change resource templates. For input D, users provide information as

quantity for multiple pre-established maintenance actions. Transportation from the factory to the construction site is included in Klimatkalkyl 7.0 with the possibility of changing the distance and fuel and, to some extent, transportation mode (Trafikverket, 2023).

2.1.2 LICCER

This tool results from the collaboration between three international universities, which makes it more flexible for modification (compared to KlimatKalkyl) (Lemperos & Potting, 2015). LICCER is an Excel-based tool that measures GHG emissions and energy use of road, bridge, and tunnel infrastructures components and traffic in road corridors (Liljenström et al., 2020). It was developed to be used in Sweden, Denmark, Norway, and the Netherlands as a decision-supporting tool to make a comparison between the life cycle impact and energy consumption of the road corridor alternatives. However, it can be used in any country by providing the required data in the model or entering the project-specific data (ibid).

According to Liljenström et al. (2020), the model provides the users with the opportunity to compare up to three road corridors by showing which corridor has the lowest environmental impact based on the CO₂ equivalent emissions and energy use and indicating environmental hotspots of each corridor. The calculation is based on the LCA method and comprises goal and scope definition, inventory data, impact assessment, and interpretation of results. The functional unit is "Road infrastructure enabling annual traffic between 'A' and 'B' over an analysis time horizon of a defined number of years." The model uses default representative data of Swedish and Norwegian construction conditions. And it is applicable for all life cycle stages except after the end of life (module D). Annual GHG emissions can be calculated based on the set lifetime by a user. LICCER was developed to be used by NRAs, and ecoinvent (one of the common LCA databases) has not been used as a source of data; therefore, it is accessible without licenses.

2.1.3 DuboCalc

Rijkswaterstaat (RWS), part of the Dutch water and infrastructure ministry, aims to be climate neutral by 2030 (Reeves et al., 2020). DuboCalc is based on the LCA method that follows ISO 14040 standards and has been developed by RWS to calculate eleven environmental impacts during the construction lifetime. These eleven impact categories are Depletion of abiotic resources, Depletion of fossil energy, Climate change, Ozone layer depletion, Photochemical oxidant formation, Acidification, Fertilization, Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, and Terrestrial ecotoxicity (PROCEEDR, 2023).

Dubocalc covers all life cycle stages, including construction (A1-A5), use and maintenance (B1-B5), end of life (C1-C4), and after the end of life (D) (PROCEEDR, 2023). It enables users to make comparisons between different options of design and materials and can be also used as part of the procurement process by RWS. This tool covers all construction and civil engineering works (not just road or infrastructure projects), and the user can insert the project-specific data or use the tool's library (reference database) (PROCEEDR, 2023; Reeves et al., 2020).

DuboCalc database consists of nationally developed Dutch EPDs, including three different databases (Reeves et al., 2020),

- Brand data that has been verified by an independent third party.
- Generic data (for non-branded material) which has been verified by an independent third party.
- Generic data (for non-branded material) which has not been verified.

The suppliers should submit their proposal based on their design description, bidding price, and Environmental Cost Indicator (MKI) which is calculated by DuboCalc. RWS will provide suppliers with the DuboCalc access, handbook, and calculation procedure and will evaluate the tenders based on the price/quality ratio (Reeves et al., 2020).

2.1.4 VegLCA

The Norwegian Public Roads Administration (NPRA) use LCA at different project stages to assist them in reaching carbon footprint reduction goal (Reeves et al., 2020). VegLCA is an Excel-based tool developed in 2015 to be used at the later stages of the project design. VegLCA can be used in material and design choices in road layers, bridges, tunnels, transportation, construction equipment, operation, maintenance, etc. (PROCEEDR, 2023).

It is developed following ISO 14040 standards and applies to A1-A4 and B4-B5 life cycle modules which are material consumptions, construction activities, operation, and maintenance (end-of-life stage is missing) (PROCEEDR, 2023). VegLCA can also be used in the procurement process and the contractors receive bonuses for using low-carbon materials and activities (Reeves et al., 2020). All projects over 51 million NOK have to use VegLCA to measure their GHG emissions (PROCEEDR, 2023).

This tool mainly covers greenhouse gas emissions; however, it can also calculate other environmental categories including acidification, eutrophication, Formation of photochemical and Energy use (PROCEEDR, 2023). Default data have been provided in the tool (such as generic average Norwegian and European data) but project-specific data can be overwritten by the user.

All of the reviewed tools are developed to measure the environmental impact of road infrastructure in European countries. However, just one of them, DuboCalc, has considered noise and safety barriers as part of infrastructure components (it is also not clear if it can calculate the environmental impact of them as a standalone object).

2.2 Roadside noise barriers and related sustainability studies

Noise barriers or noise-reducing devices (NRDs) are used to diminish undesirable noise impacting communities (C. Oltean-Dumbrava & Miah, 2016). Based on Oltean-Dumbrava & Miah, (2016) the need for NRDs rises in two situations. First, when the model of the potential road or rail predicts that the surface noise is higher than the level to be safe, or second, the condition of the existing track and road reached the level to be harmful (in case of noise pollution) for the surrounding areas. Since it is predicted that the surface noise (noise from road/rail) will increase in the coming decade; therefore, the need for NRDs will not be decreased.

Noise barriers encompass a wide range of materials and construction methods, which vary depending on the cultural and industrial background and design approaches of different countries (PROCEEDR, 2023). Figure 2.1 contains the most common noise barriers throughout the world. However, different countries adopt specific types to install. For example, in several central and southern European nations (such as Germany, Austria, The Netherlands, Belgium, Switzerland, and Italy, standardized) noise barriers made up of structural (like steel beams or concrete pillars), and acoustic elements (such as metal, timber cassettes, PVC or concrete panels) (PROCEEDR, 2023). In the United Kingdom, timber is most often erected while in Switzerland, panels made of transparent or wood cement modules are the most frequently used ones (C. Oltean-Dumbrava et al., 2012).

Noise barrier Types identified for research		
No.	Key	Type
1	SM	Steel supporting structure + Metal panels
2	SC	Steel support structure + Concrete panels
3	ST	Steel supporting structure + Timber panels
4	SG	Steel supporting structure + Transparent modules
5	C	Self-supporting concrete or brick system
6	SP	Steel supporting structure with plastic panels
7	CT	Tunnel-concrete structure
8	STu	Tunnel-steel structure
9	GT	Tunnel with transparent panels
10	GB	"Green" barrier (containing vegetation)
11	GA	Gabions (wire cage filled with graded stones)
12	EB	Earth barrier (earth mound or berm)
13	PVNB	PVNB (photovoltaic noise barrier)

Figure 2.1 Noise barrier types (Oltean-Dumbrava & Miah, 2016)

The environmental impacts of NRDs are as much as any other built structure (C. Oltean-Dumbrava et al., 2012). Based on Oltean-Dumbrava et al. (2012) estimation, a typical nose barrier in the United Kingdom is 2 or 4 km in length (one or two sides of the road) and 4 meters in height (it means it will occupy an area of 16 m²). The estimate of installation and resources costs for the timber option is 100 Euro per meter and 1.8 million Euros total respectively. The cost of aluminum or wood cement could double this cost. If the barrier contains road cover, this expenditure could be much higher. As a result, the study intended to pinpoint that the public expenditure of this scale requires the whole life cycle sustainability consideration.

The EN standards regarding the whole lifecycle of noise barriers thoroughly address technical issues, however, they cover some important environmental, few social considerations and rarely specify any economic requirements (C. Oltean-Dumbrava et al., 2012). LCA can be expanded into life cycle sustainability assessment (LCSA) to also include social and economic aspects (besides environmental) (Hauschild et al., 2018). The idea of LCSA is built on "three pillars" which comprise the environmental, social, and economic pillars.

LCSA=LCA (life cycle assessment) +LCC (life cycle costing) +SLCA (social life cycle assessment)

Quieting the Environment for a Sustainable Surface Transport (QUIESST) was a three-year project run by 13 EU partners from 8 different countries, one deliverable of this project (WP6) was to provide the sustainability assessment framework and method for noise reduction devices (NRDs) (C. Oltean-Dumbrava et al., 2016). The need for this project was recognized by the European Union (EU) to form a sustainable agenda for procurement agencies, policymakers, and industrial professionals/designers (C. Oltean-Dumbrava et al., 2012). The goal was to evaluate the sustainability of the surface (roads and rails) noise reduction devices. Sustainability was defined as an optimal combination of technical, environmental, social, and economic indicators within the whole life cycle of the devices, including production, construction, maintenance, and demolition (see Figure 2.2).

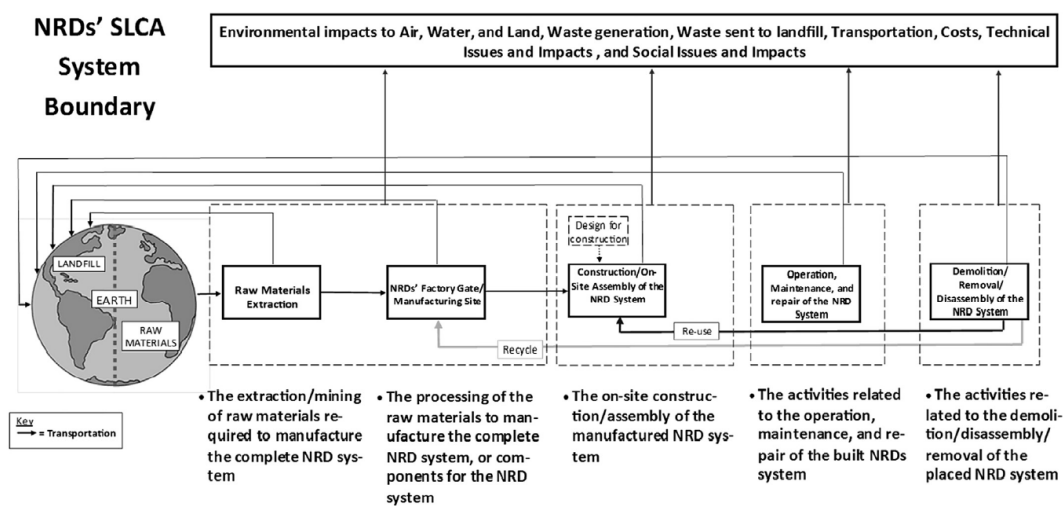


Figure 2.2 The NRDs' sustainability life cycle assessment (SLCA) (C. Oltean-Dumbrava et al., 2016)

The aim of Work Package 6 of QUIESST was to promote the sustainability of noise reduction devices (NRDs) (C. A. Oltean-Dumbrava, 2012). C. A. Oltean-Dumbrava (2012) defined a generic set of sustainability KPIs (key performance indicators) for NRD projects per four sustainability factors, including social, technical, environmental, and economic (Figure 2.3). Since the assessment of sustainability is a relative issue, it should be done based on a set of alternatives or based on a defined baseline. This project chose the baseline and implemented the MCDM (multi-criteria decision-making) tools for assessing the sustainability of one selected NRD to provide the stakeholders with a sustainable assessment approach to implement and make informed decisions.

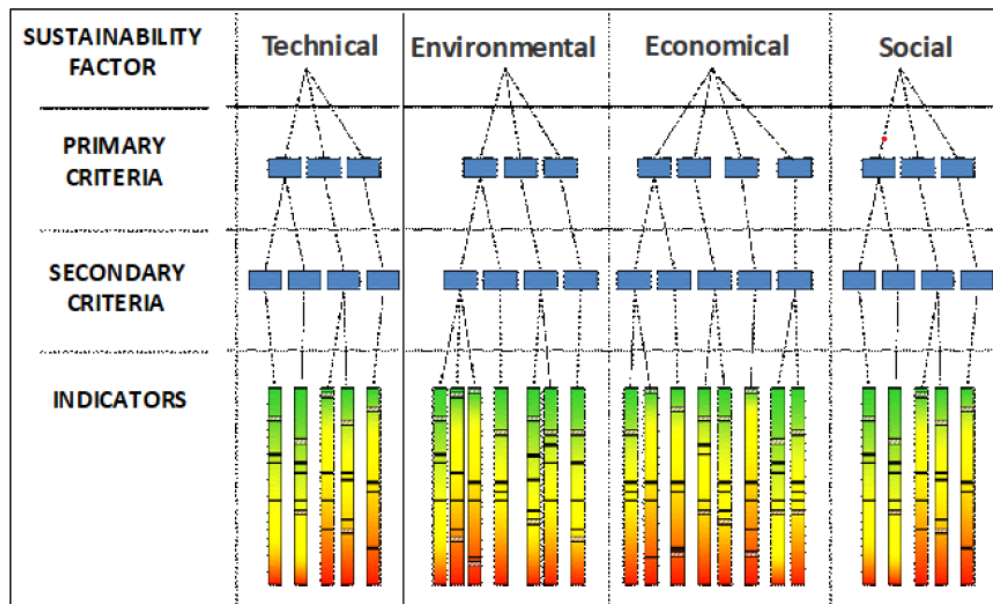


Figure 2.3 Top-Down and bottom-up approach to define the framework to identify criteria and indicators for noise barriers used in the project QUIESST

C. Oltean-Dumbrava & Miah (2016) ranked the sustainability of 13 available NRDs (Figure 2.1) based on using multi-criteria analysis techniques. The ranking was done within the MCDM (multi-criteria decision-making) framework based on overall and individual environmental, social, economic, and technical performances. The results showed that the green options are not always the most sustainable ones and ranking can be different based on the defined indicators from various aspects (social, environmental, technical, and economic). However, these rankings will help the decision maker by providing information that is not site specific to decide on their own case based on the options and important factors.

3 Methodology description

The concept of LCA originated in the 1960s, during a period when environmental deterioration, particularly the restricted availability of resources, began to raise concerns (Hauschild et al., 2018). Today, LCA is defined as "a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use stages, to waste management" (ISO Standard 14040, 2006).

The complexity of product life cycle inventories increased over time, leading to a shift from solely tracking the physical flows to converting inventory findings into potential environmental impacts (Hauschild et al., 2018). Essentially, the resource uses and emissions data collected during the assessment were utilized to compute a series of indicator scores for the evaluated product, highlighting its contributions to various impact categories like climate change, eutrophication, and resource scarcity (ibid).

LCA methodology is structured according to the ISO 14040 framework and will be discussed in this section. Therefore, the reference for all parts of methodology definitions is ISO 14040 (Figure 3.1), which is explained by Hauschild et al. (2018) otherwise it will be mentioned.

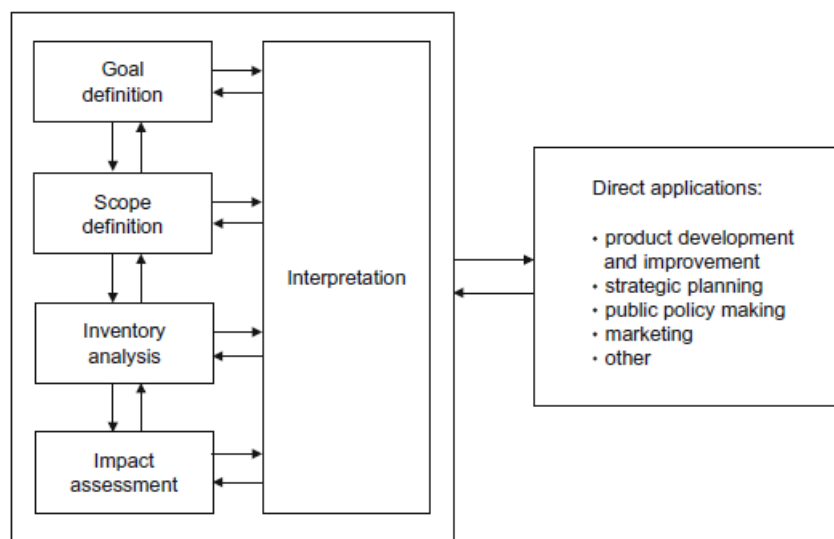


Figure 3.1 Framework of LCA modified from ISO 14040 standard (Hauschild et al., 2018)

3.1 Goal definition

The purpose and intention of the study should be discussed and elaborated in detail in the goal definition since other stages must be consistent with it. Based on the ISO standard, this step comprises the six following aspects.

1. Intended application of the results
2. Limitations because of methodological choices
3. Target audience
4. Decision context and reasons for carrying out the study
5. Comparative studies to be disclosed to the public
6. Commissioner of the study and other influential actors

3.1.1 Intended application of the results

Intended application of the LCA results can lead to comparing environmental impact, identifying hot spots, detecting improvement potential, documenting the environmental performance (i.e., EPD, Environmental Product Declaration), developing criteria for eco-labelling, and developing environmental considering policies. Determining the intended application of LCA will affect the later phase, such as sourcing inventory data and interpretation.

3.1.2 Limitation due to methodological choices

Limitation due to methodological choices show what LCA results can and cannot be used for. This part will mention the limitation that goal and scope has made.

3.1.3 Decision context and reasons for carrying out the study

The reason for the study should be well connected to the intended application. To clarify the difference between the intended application and reasons for conducting the study, the first one describes what a study does, and the second one should point out why a study is done.

3.1.4 Target audience

The audience can be companies, organizations, NGOs, customers, manufacturers, product developers, and others to whom the results of the study are supposed to be communicated. The audience of the study extensively will affect the technical level of reporting, level of documentation details, and interpreting results.

3.1.5 Comparative studies to be disclosed to the public

If the LCA study is aimed to be acknowledged to the public, ISO standards identify specific requirements on how it should be documented and conducted and an external review process.

3.1.6 Commissioner of the study and other influential actors

It should be stated who has commissioned and financed the study and other parties/organizations who influence the study. It highlights the potential of interest conflicts to the readers of the study.

3.2 Scope definition

In Life Cycle Assessment (LCA), defining the scope is crucial as it identifies the specific product or system to be evaluated and outlines the approach for conducting the assessment. The scope definition, along with the goal definition, provides a clear direction for subsequent phases of the LCA, including Inventory analysis, Impact assessment, and Interpretation. Moreover, the scope and goal definitions are integral to reporting the LCA study, as they ensure that the methods, assumptions, and findings are transparently presented to the intended audience.

Determining the following steps is central to doing a scope definition.

1. Object of the assessment (Functional unit)
2. LCI modelling framework and handling of multifunctional processes
3. System boundaries
4. Representativeness of LCI data

5. Basis for the impact assessment

3.2.1 Object of the assessment (Functional unit)

The LCA study should begin by defining the user's perspective of the functions since two or more product systems comparison is only fair and reasonable if the products provide the same or similar functions to the user. In order to enable a quantitative comparison of different products for providing a particular function, it is important to have a complete understanding of the functions offered by the alternative product systems. This understanding is then used to establish a functional unit, which outlines both the qualitative and quantitative aspects of the function.

3.2.2 LCI modelling framework and handling of multifunctional processes

To realize the reason for the existence of different LCI modelling frameworks, it first should be mentioned that a product system may serve functions beyond its primary functions, known as secondary functions. These functions are usually irrelevant to the product's users and do not contribute to its obligatory properties. The presence of secondary functions highlights the need for various LCI modelling frameworks to address the unique aspects of different product systems. To deal with multifunctionality problems, ISO 14044 gives several solutions. One of its solutions is allocation. Allocation is "dividing the inputs and outputs of the multifunctional process or system between the different products or functions." Attributional and consequential are the two main LCI modelling frameworks. During LCA development in the early to mid-nineties, attributional LCI modelling was the common method. The attributional modelling intention is to show the product system independently from the larger technological and economic context. Using average processes in the background system (using a market mix) is also linked to attributional LCA. While the development of consequential LCI modelling in the early 2000s aimed to address the limitations of attributional LCA, which tried to isolate a product from the larger economy. The goal of consequential modelling is to describe the economic changes resulting from the introduction of the product system being studied. Figure 3.2 presents the meaning and differences between attributional and consequential frameworks.

LCI modelling framework	Question to be answered	Handling of multifunctional processes when subdivision is not possible		Modelling of background system
		Before ILCD	ILCD	
Attributional	What environmental impact can be attributed to product X?	Allocation	System expansion or allocation	Average processes
Consequential	What are the environmental consequences of consuming X?	System expansion	System expansion	Marginal processes

Figure 3.2 Attributional and Consequential modelling framework (Hauschild et al., 2018)

3.2.3 System boundaries

The boundaries of a system are used to separate the product from its economic and environmental environment. To make sure that the product system model is complete and aligned with the study's objectives, completeness requirements are considered. These requirements help determine which processes should be considered within the system boundaries. It is important to note that the boundaries of the system can significantly impact the results of life cycle assessment (LCA) as they dictate the unit processes that should be measured to quantify the environmental impacts.

3.2.4 Representativeness of LCI data

LCA strives to accurately depict the physical world, meaning the model should show reality as much as possible. To achieve this, the unit processes used in modelling the product system should be representative of the actual processes, specifically in the case of attributional LCA.

3.2.5 Basis for the impact assessment

Based on the ISO 14044 standard governing LCA, the impact categories chosen for an LCA must encompass a comprehensive range of environmental issues relevant to the product system under examination, taking into account the study's objective and scope. This implies that all environmental impacts in which the product system plays a significant role should be incorporated into the impact assessment unless the goal definition specifies differently.

3.3 Inventory analysis

Inventory analysis is the most time using step of LCA. The primary function is to gather and assemble data regarding the basic components of all processes within the product system(s), utilizing various sources. The outcome is compiled and serves as the foundation for the succeeding life cycle impact assessment stage.

After defining the scope and identifying the processes included in the system boundaries, these modules' data collection needs to be carefully planned and executed. The aim of the planning is to balance the attempt of collecting data with the importance of the corresponding data and information.

3.4 Impact assessment

It is crucial to remember that the impacts evaluated during the life cycle impact assessment (LCIA) phase ought to be construed as potential impacts rather than real impacts, and they should not be seen as exceeding safety margins or thresholds or posing a risk, as they are merely estimations. They express the potential impacts linked to the life cycle of a functional unit. This involves integrating inventory data across different locations and periods, which can vary. The impact assessment data does not provide information about the specific circumstances of the environment being affected, such as exposure to other substances from different product systems.

Based on the ISO 14040/14044 standard the mandatory steps for LCIA are:

1. Selection of impact categories
2. Classification
3. Characterization

3.4.1 Selection of impact categories

The impact categories selection intention is to determine the most suitable and essential ones for a particular aim. To facilitate the acquisition of data on related elementary flows in the inventory analysis, the impact categories selection should align with the study's purpose and should be completed during the scope definition phase.

3.4.2 Classification and Characterization

To classify, the individual inputs of the life cycle inventory (LCI) will be attributed to the corresponding impact categories they contribute to. For instance, the release of CO₂ into the air would be linked to climate change, while the use of water would be connected to the water consumption impact category. However, this process can be challenging due to certain substances having multiple impacts in two ways. First, some substances may cause multiple concurrent impacts, such as SO₂, which causes both acidification and human respiratory issues. Second, some substances can have an adverse effect, which then triggers a chain reaction, such as SO₂ leading to acidification, which mobilizes toxic heavy metals in the soil that can harm both humans and ecosystems. This step necessitates a profound comprehension of environmental impacts and expert knowledge, which is usually handled by LCA software through pre-programmed classification tables rather than by the LCA practitioner.

In the characterization step, all flows will be evaluated based on their contribution to the specific impact category. To clarify, the elementary flows which have been classified regarding each impact category will be multiplied by their characterization factor to be expressed in the same specific unit. For example, CH₄ and CO₂ are related to global warming and CO₂ is the global warming representative unit. Therefore, the attribution of CH₄ to global warming will be measured based on the CO₂ equivalent.

If the impact assessment relies on midpoint indicators, then the classification process involves categorizing the inventory outcomes into groups of substance flows that can potentially lead to the same environmental impact. To achieve this, characterization factors specifically created for the relevant impact category are applied. For instance, all substances' elementary flows that might cause cancer in humans will be categorized under the same midpoint category known as "toxic carcinogen," and their contribution to this impact will be determined through characterization calculations (Figure 3.3).

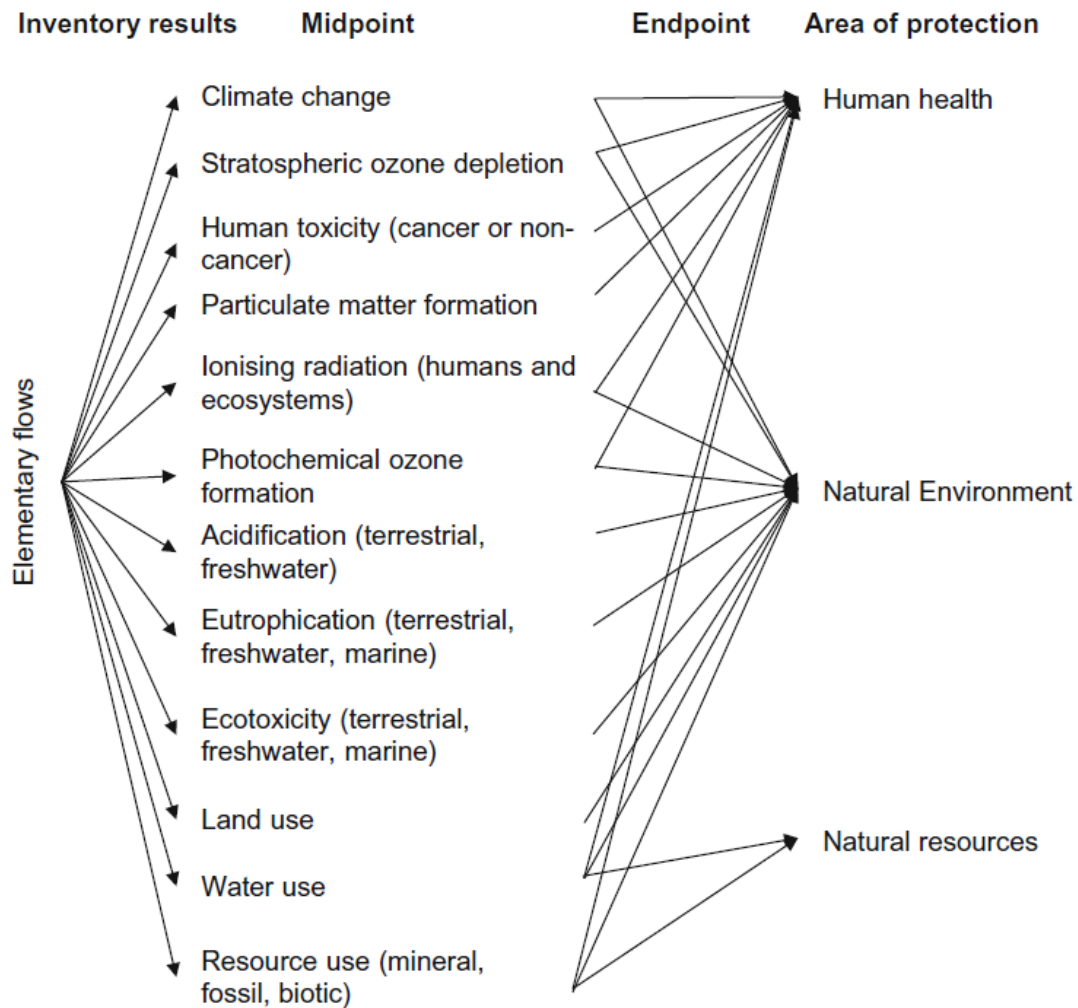


Figure 3.3 Elementary flows from the inventory results to the indicator results at the midpoint and endpoint level for 15 midpoint impact categories and 3 areas of protection (Hauschild et al., 2018).

3.5 Interpretation

In the LCA process, interpretation is the stage where the outcomes of the other phases are analysed together and evaluated with regard to the uncertainties associated with the data used and the assumptions made throughout the study. The interpretation stage shows the LCA's conclusions understandably and assists the study's users in assessing its reliability and potential weaknesses based on any limitations that have been identified (Figure 3.4).

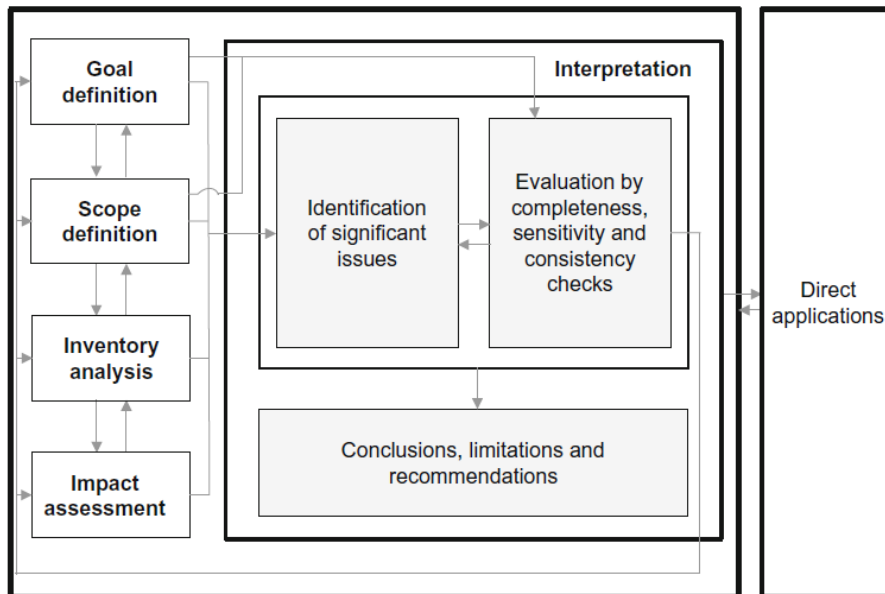


Figure 3.4 Interpretation phase elements and their relations to each other (Hauschild et al., 2018)

3.5.1 Identification of significant issues

The initial part of life cycle interpretation aims to scrutinize the outcomes of the preceding LCA phases to identify the most critical environmental concerns, which can alter the final LCA results. These issues can be related to taken assumptions and methodological choices, inventory data for critical life cycle processes, or the other factors in the impact assessment. The goal is to pinpoint the most significant issues that could potentially influence the LCA's conclusions.

3.5.2 Evaluation

The evaluation is crucial as it serves as the foundation for drawing conclusions and making recommendations. This step is conducted through an iterative process with key issues detection to assess the reliability and consistency of the identification part results.

To determine the extent to which the available data is comprehensive for the crucial identified impacts and processes, completeness checks are carried out for both the inventory and the impact assessment. In cases where relevant information is absent or not complete for some of the critical processes or significant elementary flows or impact categories, the importance of that information in meeting the LCA's purpose and scope must be examined.

The consistency check is an important step in LCA to ensure that the made assumptions, used methods, and data in the study are in line with the goal and scope. It investigates the inventory data quality, including its representativeness (time, geographical and technical related), appropriateness of the chosen unit process, and uncertainty. The check also ensures that allocation choosing, system boundary defining, and impact assessment are consistently applied to all compared product systems when conducting comparisons (In the current thesis this part will be covered within the discussion).




4 Applied method and results

In this section, what has been done in each step of LCA for this thesis will be presented and discussed.

4.1 Goal definition

For this project, three noise barriers (and variants for two of them) have been chosen to conduct comparative LCA (Table 4.1). This selection is done between the common noise barriers in Europe in the reviewed studies (Figure 2.1) and the availability/accessibility of their data.

Table 4.1 Chosen noise barrier for comparative LCA

Key	Name	Description	Picture
ST	Steel supporting structure + transparent panels	noise barrier made of structural elements (steel posts + base plate and anchor bolts) + acoustic elements made of transparent panels (transparent sheets made of, polycarbonate).	
SM	Steel supporting structure + metal panels	noise barrier made of structural elements (steel posts + base plate and anchor bolts) + acoustic elements made of a metallic cassette (aluminium) with an inner sound-absorbing material (rock wool or polystyrene foam)	
SP	Steel supporting structure + plastic panels	noise barrier made of structural elements (steel posts + base plate and anchor bolts) + acoustic elements made of plastic (PVC) cassette with an inner sound absorbing material (rock wool or polyester foam).	

The intended application of this study is:

- Comparing the whole life cycle environmental impacts of 5 different kinds (ST, SM, SP + 2 variations for SM and SP if their inner sound absorbing material is rock wool or polystyrene) of roadside noise barriers with a focus on CO₂ equivalent emissions.
- Comparing the results based on different end-of-life scenarios.
 - The first scenario is using virgin material which all will be disposed of at the end of life.
 - The second scenario is recycling material at the end of a cycle (based on the possible recycling rate for each material) to be consumed in the second and third cycles.
- Identifying life stages/modules and activities with the highest environmental impact based on GWP.

The limitation of this current thesis consists of the following points.

- It is assumed that all chosen noise barriers are fulfilling the necessary technical requirements. Therefore, their noise reduction ability has not been considered in defining functional units and their environmental impacts cannot be compared based on their technical (noise reduction) performance.
- The presented results show the environmental impacts of noise barriers structure and panels. Hence, the overall impact of noise barriers, which consist of foundation will be different.
- To have the exact environmental impact, the data can be collected from the product developer and manufacturer. In the current study, in some cases because of the lack of access to first-hand data, literature and expert estimation has been used.

This thesis aims to aid in the development of a web tool for the PROCEEDR project. This tool is going to support NRAs in creating effective and sustainable strategies for transitioning from a linear to a circular economy concerning roadside infrastructure.

The audience is the same as the PROCEEDR project. Hence, as mentioned before, the primary audience is NRAs. However, to improve the current conditions of existing roadside noise barriers, manufacturers can also be considered as secondary audiences.

It is a comparative study for giving a better insight into PROCEEDR tool developers and will be publicly available. PROCEEDR project has been run and financed by NRAs. Nevertheless, this project is conducted independently and is not financed by any party.

4.2 Scope definition

The functional unit is **1m² of the roadside noise barriers during the lifetime of 50 years**. The noise reduction ability has not been considered since all chosen noise barriers have been selected from the standard types which is assumed they are fulfilling their technical requirements. Therefore, this assessment is meant to provide a basis to just compare noise barriers' environmental impacts.

For the second end-of-life scenario (using virgin material for the first cycle and recycling part of it to be used again in the second and third life cycles), the cut-off allocation has been used. This involves assigning the environmental impacts of each process within a product's life cycle to that product. The only difficulty with this method is determining where the boundaries lie between the different life cycles (Ekvall et al., 2020). Based on Ekvall et al. (2020), the cut-off is the simplest approach to model recycling, which is recommended by the international system for Environmental Product Declarations (EPD); however, the difficulty lies in defining the boundary between various lifecycles. The boundary between life cycles is assumed when the product has its lowest market value. Figure 4.1 shows the applied method in the second scenario. E_1 , E_2 , and E_3 are environmental burdens of the products (in this case, life cycles of 50 years). As the figure shows, the environmental impact of raw material will be assigned to the first cycle, recycling processes impacts will be allocated to the second and third cycles, and disposal to the last (third) cycle.

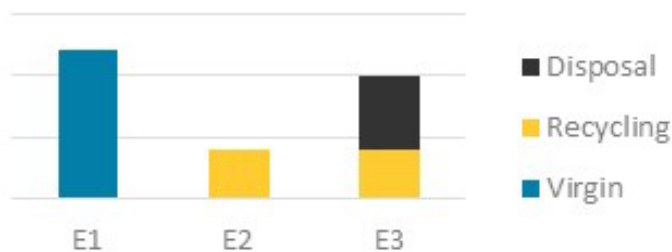


Figure 4.1 The simple cut-off method applied in the current research (Ekvall et al., 2020)

This LCA aims to find the environmental impacts of the current noise barriers to detect the hot spots modules and activities. Therefore, it is an attributional LCA.

Figure 4.2 shows the included modules in the system boundary (cradle to cradle) of this study. Based on the EN_15804:2012 standard, these modules are:

- A1-A3: Includes raw material extraction and processing or secondary material processing (in the second end-of-life scenario), material transporting to the manufacturers and manufacturing processes,
- B2 and B4: Includes regular surface cleaning and replacement of the noise barriers modules during their lifetime,
- C2-C4: Includes transportation to the waste processing, waste processing for recycling (in the second end-of-life scenario), and waste disposal after noise barriers lifetime,
- D: Includes Net benefits and loads from recycling end of waste materials (it has been considered only in the second scenario)

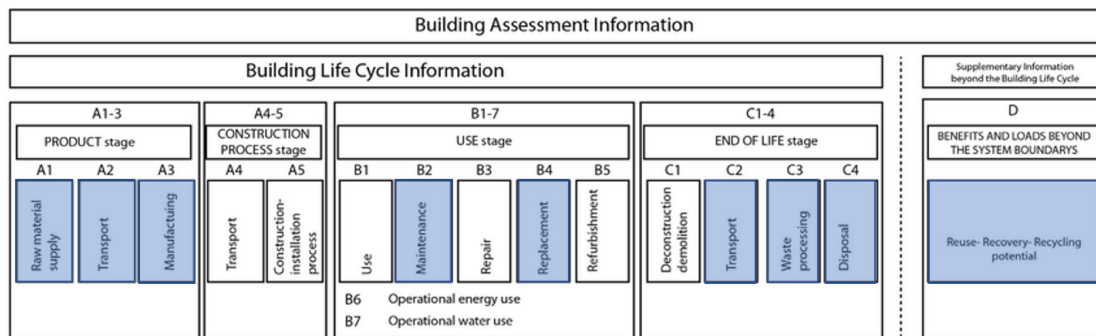


Figure 4.2 Included modules in this study, life cycle stages and modules are defined based on EN_15804:2012 standard

For this project, the most recent available data from ecoinvent 3.8, EPD, literature, and expert estimation have been used to assess the noise barriers' environmental impact. By using ecoinvent data, all the upstream and downstream processes have been included and allocation methods have already been conducted and done by cut-off whenever it is necessary.

The geographical scope is Sweden, however since the country-specific data are not always available in ecoinvent, the closest one has been considered. To clarify, mostly European data has been used (or Global in case of unavailability) unless country-specific are available.

For this research, 10 common environmental impact categories (Table 4.2) have been chosen to assess the environmental loads of noise barriers during their whole lifecycle using the ReCiPe midpoint (h) method. However, for further investigation and detection of hotspot modules and activities, just Global warming potential (GWP) will be considered since it is an important indicator for the NRAs.

Table 4.2 Chosen environmental impact to show the overall impact assessment

Category	Unit
climate change - GWP	kg CO ₂ -Eq
fossil depletion - FDP	kg oil-Eq
freshwater eutrophication - FEP	kg P-Eq
marine eutrophication - MEP	kg N-Eq
ozone depletion - ODP	kg CFC-11-Eq
terrestrial acidification - TAP	kg SO ₂ -Eq
human toxicity - HTP	kg 1,4-DCB-Eq
particulate matter formation - PMFP	kg PM10-Eq
photochemical oxidant formation - POFP	kg NMVOC
water depletion - WDP	m ³

4.3 Inventory analysis

Among the stages of inventory analysis, identifying the process for the LCI model and data collection are the most relevant ones to the current study.

4.3.1 Identifying processes for the LCI model

Figure 4.3 shows the flowchart of the LCA study. For the first scenario, it is assumed that all materials will be 100 percent disposed of after the end-of-life (50 years); while the orange module is added for the second scenario in which the recyclable amount of each material (based on statistics and related studies that will be mentioned later) will be treated for recycling to be used in the next cycle and the rest will be disposed of.

All materials are 100 percent virgin in the first cycle of both scenarios, except steel. Scrap steel has been considered as an input for galvanized steel. Nevertheless, steel is the common structure for all chosen noise barriers, therefore, it will not affect the comparison results.

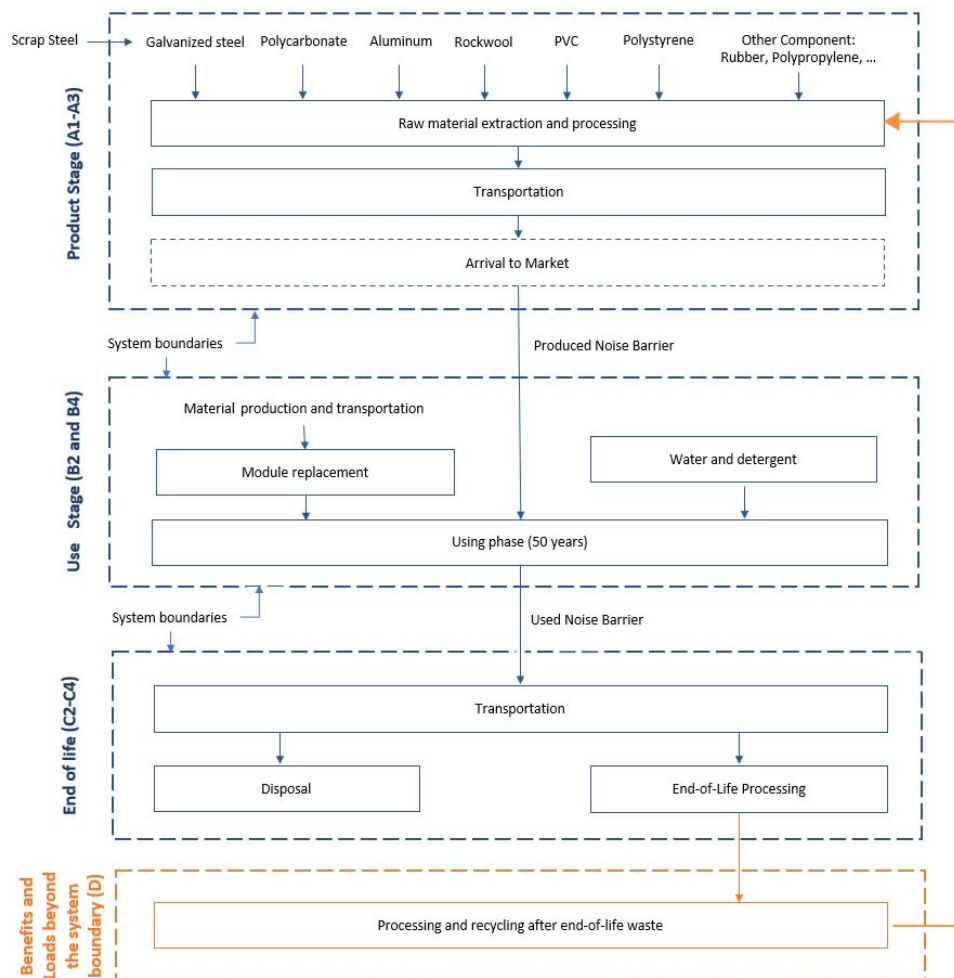


Figure 4.3 Flowchart of the study

4.3.2 Data Collection

The database used for this project is ecoinvent version 3.8. and inventory data are modelled using OpenLCA version 1.11.0. As Figure 4.3 shows, several types of data are required to be gathered regarding materials production, needed activities and materials during the lifetime, end-of-life treatment, and recycling rate for each material. All the mentioned data and the assumption that have been taken are provided in Appendix A. However, in what follows, the points regarding the data-gathering process and assumptions for each part will be discussed.

4.3.2.1 Materials Production

For ST (steel post supports and transparent panels), there is an available EPD from Hammerglass manufacturer¹, which is made of polycarbonate and steel posts. The quantity bill of materials has been taken from the EPD. It should be mentioned that the electricity consumption of the Hammerglass was not available separately. However, the noise barrier is one of the several products of the manufacturer, therefore the manufacturer's electricity allocation of this product is assumed to be neglectable and has been excluded. For other noise barriers, SM (steel post supports and metal panels), and SP (steel post supports and plastic panels), expert estimation of materials quantities is the base of data collecting.

Due to the unavailability of the exact processes for some of them in ecoinvent, assumptions have been made and equivalent processes have been taken. For example, instead of Hot-dip galvanizing process, "*zinc coat, pieces*" have been chosen, which is the main activity of galvanizing. All materials consist of 100% raw materials in the first cycle (except steel). The highest amount of primary aluminium in aluminium production is in "*aluminium, primary, cast alloy slab*" which is 95%.

In some cases, the materials units were not matched with the same process in the ecoinvent. In those cases, the assumed density or thickness of that product has been used for unit conversion.

The market provider has been chosen for all processes to cover the average transportation within each process. The geographical boundary is Europe or Sweden (in case of availability of country-based data). However, if providers within Europe were not available, a global provider has been chosen.

The material substitutes, assumed density or thickness and chosen providers can all be found in Appendix A – Modelled inventory data.

4.3.2.2 Cleaning and Replacement

The expected lifetime for the noise barriers is 50 years. However, regular replacement might be needed because of accidents, fire, vandalism, and so on. Therefore, the replacement of acoustic elements (rock wool and polystyrene) and their panels (aluminium or PVC) is assumed to take place every 20 years for 10% of the noise barrier modules. This period for transparent modules (polycarbonate) is 15 years and for steel structures is 25 years. This estimation is based on the expert opinion and the amount of material replacement is also provided in Appendix A.

Cleaning of the barriers will be done with water and household mild detergent (Hammerglass, 2023). Assumptions regarding cleanness are 3 times a year for the transparent barrier and 2 times a year for the others.

4.3.2.3 End of Life and Recycling Rate

As it was mentioned earlier, all material will be disposed of in the first scenario after the end of life. However, in the second scenario, based on the recycling rate of each material, part of it will be recycled for the next cycle and the rest will be

¹ <https://www.environdec.com/library/epd5712>

disposed of. These processes will be done for the second and third cycles. In what follows, the recycling rate and treatment for each material will be discussed. The construction industry has the second largest contribution to plastic consumption; however, not all the sorted plastic waste will be recycled for new one's production. For example, if they do not meet the requirements for cleanliness during pre-processing, they will be sent for another type of treatment (usually incineration with energy recovery) (Fråne et al., 2022). Some of them will be exported for treatment processing. Based on Fråne et al. (2022) only 2.5 percent of plastic generated by construction goes to recycling (Figure 4.4)

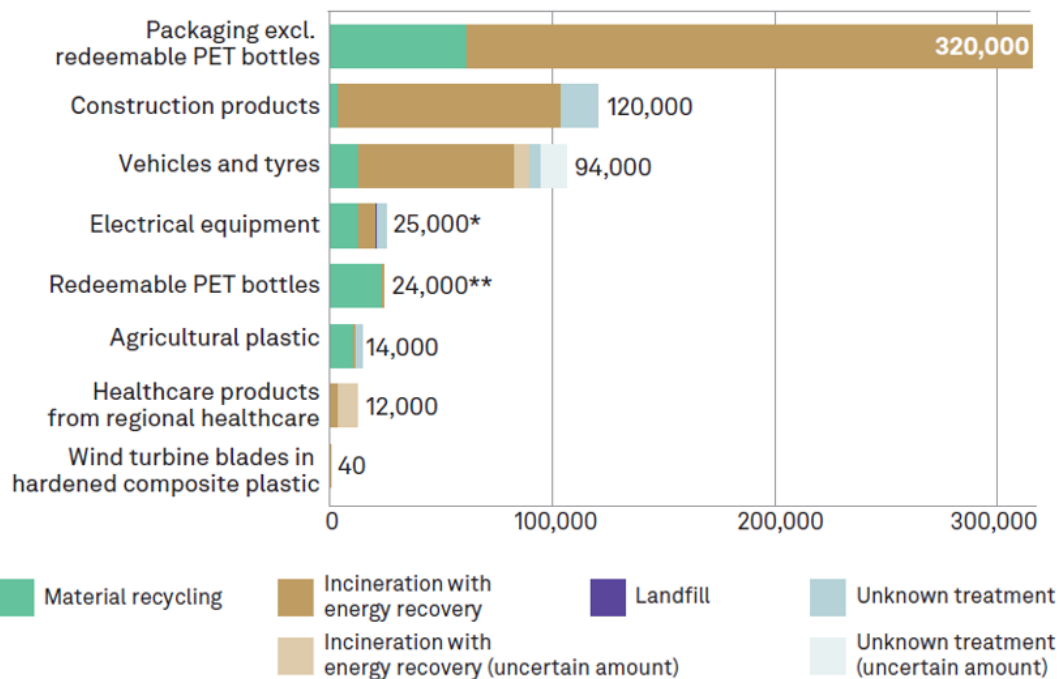


Figure 4.4 Plastic waste per product category, divided by waste treatment (tons)(Fråne et al., 2022)

For this thesis, the recycling rate for all kinds of plastic, including polycarbonate, polystyrene, rubber, and polypropylene, is assumed to be the same as the recycling rate for construction plastic products in Sweden, which is 2.5 percent, and the rest will be incinerated (as it is the common treatment based on Figure 4.4). For those 2.5 percent that is going to be recycled "*plastic granulate, unspecified, recycled*" process from ecoinvent has been considered.

Based on the European Aluminium Association, the recovery rate for aluminium is 95%, and the rest 5% will be landfilled (Hydro Aluminium Extrusion, 2021). The same rate has been applied to this project. For 95% aluminium in the second and third life cycle, "*aluminium scrap, post-consumer, prepared for melting*" from ecoinvent has been taken into account and the energy consumption for the melting process of aluminium scrap was estimated as 6.07 MJ/kg (Adeniji & Waheed, 2021).

The sustainability report of one of the biggest rock wool producers¹ has stated that the amount of recycled content in their product is 25% (ROCK WOOL, 2020). Based on this statistic, 25% of the used rock wool in latter cycles is assumed to be produced from used material and the electricity consumption for the crusher,

¹ <https://www.rockwool.com/group/>

hammer mill, extruder, washer, and dryer processes is estimated at 6659.1 KJ/kg (Väntsi & Kärki, 2015).

4.4 Impact assessment

The selected impact categories and their reference units are mentioned earlier in the scope definition (see Table 4.2). However, the focus for the hotspot detection will be only on global warming potential, since it's the main interest of NRAs and is aligned with the aim of several countries which are going to be CO₂ neutral soon (such as Sweden which has aimed to be CO₂ neutral until 2045). The potential effect of each category is calculated by applying the ReCiPe midpoint (h) method. In the following parts, a short description will be given for the chosen impact categories based on Klöpffer et al. (2015).

4.4.1.1 Climate Change - GWP

Climate change refers to the climate system warming caused by human actions. The primary contributor to this phenomenon is the release of greenhouse gases (GHGs), which results in a rise in the level of radiative forcing. LCIA methodologies currently only consider GHGs as the climate-forcing agent. As a result, the atmosphere and oceans' temperatures increase, leading to various high-level consequences like rising sea levels, severe weather events, and changes in rainfall patterns and will cause damage to both human health and the quality of ecosystems. The main GHGs emission from human activities are carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). CO₂ is the reference substance of GWP which means the cumulative value of other substances will be calculated as CO₂ equivalent.

4.4.1.2 Fossil Depletion – FDP

The abiotic resource use category in LCA deals with the environmental issues regarding resource consumption same as metals, minerals, fossil and nuclear energy. Fossil depletion just focuses on the consumption of fossil fuels and can be a useful assessment tool when the stakeholders' interest is mostly fossil fuel consumption during the product life cycle.

4.4.1.3 Freshwater and Marine Eutrophication – FEP & MEP

Eutrophication means nutrients over-supplying, which leads to ecosystem alternation and is caused by nitrogen and phosphor increasing in terrestrial and aquatic ecosystems. It is necessary to divide fresh and marine water since freshwater input will not change the marine water's salinity. Freshwaters are usually limited by phosphorus, however, sometimes nitrogen or even iron might be co-controlling, but it is more probable that, yet phosphorus is limiting. On the other hand, the eutrophication of marine water is more complicated, but generally, it is nitrogen limited.

4.4.1.4 Ozone Depletion – ODP

The ozone layer has a crucial function in regulating Earth's conditions. However, emissions of chlorofluorocarbons (CFCs) and other halocarbons have significantly depleted it. Consequently, more UVB radiation reaches the surface, causing several detrimental effects on human and ecosystem health. Although rising human-generated nitrous oxide (N₂O) emissions could impede the ozone layer's improvement, the aggravating influence of methane (CH₄) and carbon dioxide (CO₂) emissions will outweigh this potential threat.

4.4.1.5 Terrestrial Acidification - TAP

The sediment of inorganic substances onto the Earth's surface, including sulphur and nitrogen oxides, through atmospheric processes is the primary cause for acidification in terrestrial and freshwater, and to a lower degree in (coastal) marine ecosystems. This process can ultimately lead to changes in biodiversity. By following the cause-effect pathway, the environmental impact of these chemicals can be modelled up to the point where biodiversity is negatively impacted (endpoint).

4.4.1.6 Human Toxicity – HTP

During a product's lifecycle, chemicals are released into the environment, increasing the chemical accumulation in air, water, soil, and biota. Humans can be directly exposed to these chemicals by inhaling air and consuming water, or indirectly through bioaccumulated chemicals in the food chain. Therefore, it is crucial to consider exposures, including consumer products, when examining the entire cause-effect pathway, which encompasses the release of hazardous substances and the resulting impacts on human health. The human toxicity category is "facing the challenge of having to characterize several tens of thousands of chemicals of which roughly 100,000 may play an important industrial role."

4.4.1.7 Particulate Matter Formation – PMFP

Ambient particulate matter (PM) is regarded as a crucial environmental stressor in terms of its impact on human health. PM has been associated with severe adverse health consequences, including lung cancer, reduced life longevity, respiratory and cardiovascular diseases, mortality, diabetes, and adverse birth outcomes. Precursors such as sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH₃), semi-volatile, and volatile organic compounds contribute to secondary PM formation.

4.4.1.8 Photochemical Oxidant Formation – POFP

The photochemical oxidants are mainly O₃ and will increase as a result of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC) emissions in the atmosphere. Ozone also happens in the ozone layer, which is beneficial by filtering ultraviolet light from the sun, but the focus of this part is ground-level ozone, which is harmful to various living organisms and materials. However, the impact of ozone on material corrosion has not been widely studied in life cycle impact

assessment (LCIA). Instead, the focus has been on its impact on crops, ecosystems, and human health. Ozone has the potential to cause respiratory irritation and related various health problems, including increased mortality. It can also harm vegetation, leading to reduced productivity and biodiversity of crops, and ultimately affecting ecosystem services.

4.4.1.9 Water Depletion - WDP

The effects discussed in this context refer to situations where both ecosystems and humans are deprived of water, and where the potential harm caused by it extends to future users as well. The water cycle in the short term is mainly driven by evaporation from the ocean, precipitation on land, and runoff in rivers. However, groundwater and lakes are essential for assessing the impact of competition over water use, as they play a significant role in the long term. Water depletion would lead to biodiversity loss, reduced availability of resources for future generations, and human health problems (the last one can happen due to lack of access to safe water, not necessarily water depletion).

As mentioned earlier, in the current study, the ReCiPe midpoint (h) method has been applied, therefore, the classification and characterization are done automatically by the software (OpenLCA 1.11.0).

4.5 Interpretation

In this thesis, the focus of the identification of the significant issues will be dominance analysis, which ranks the stages and processes based on their environmental contributions.

Figure 4.5 and Figure 4.6 present the comparative environmental impacts of the chosen noise barriers based on 10 different impact categories and two scenarios (with or without recycling). The exact number of each potential is also provided in the tables (Appendix B – Environmental impacts).

The SM noise barriers have almost the highest environmental impacts in all categories in the first scenario (where all materials are primary) (Figure 4.5) while they are the greenest option when recycling materials has been considered (Figure 4.6).

The results show less variation in other barriers. Although the overall emissions are different, they almost follow the same pattern in both scenarios. The impact of both SP noise barriers (PVC panels) is mostly so close and comparable and ST barriers (polycarbonate) in most categories have a higher impact in comparison to SP (in all categories except freshwater eutrophication, Human toxicity, and water depletion).

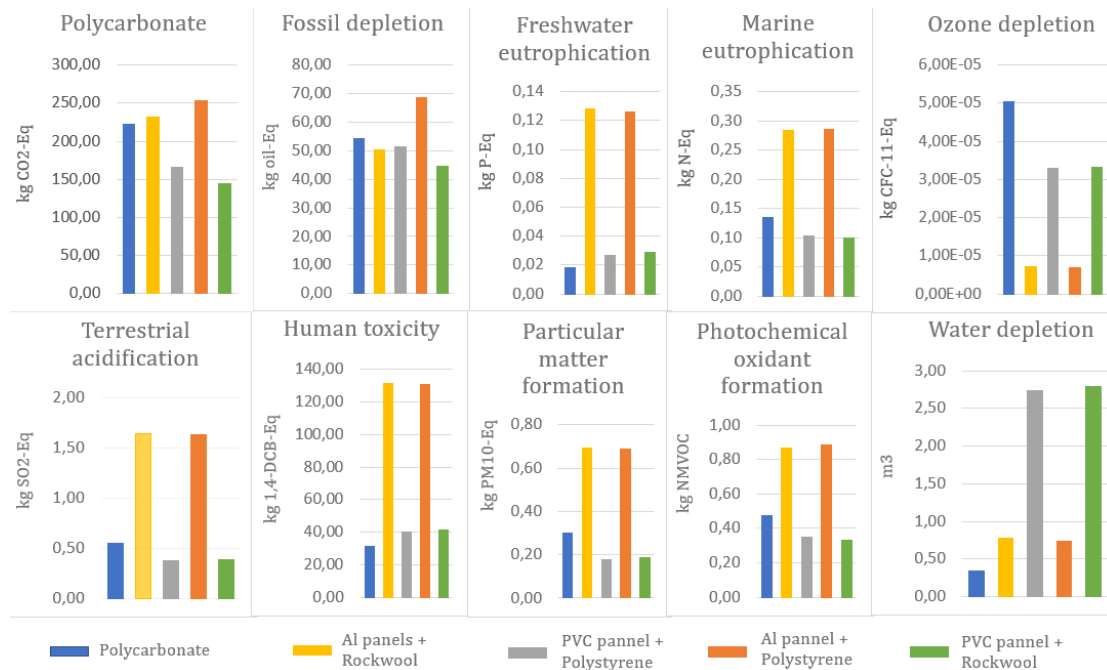


Figure 4.5 Environmental impacts of the noise barriers' whole cycle, the first scenario

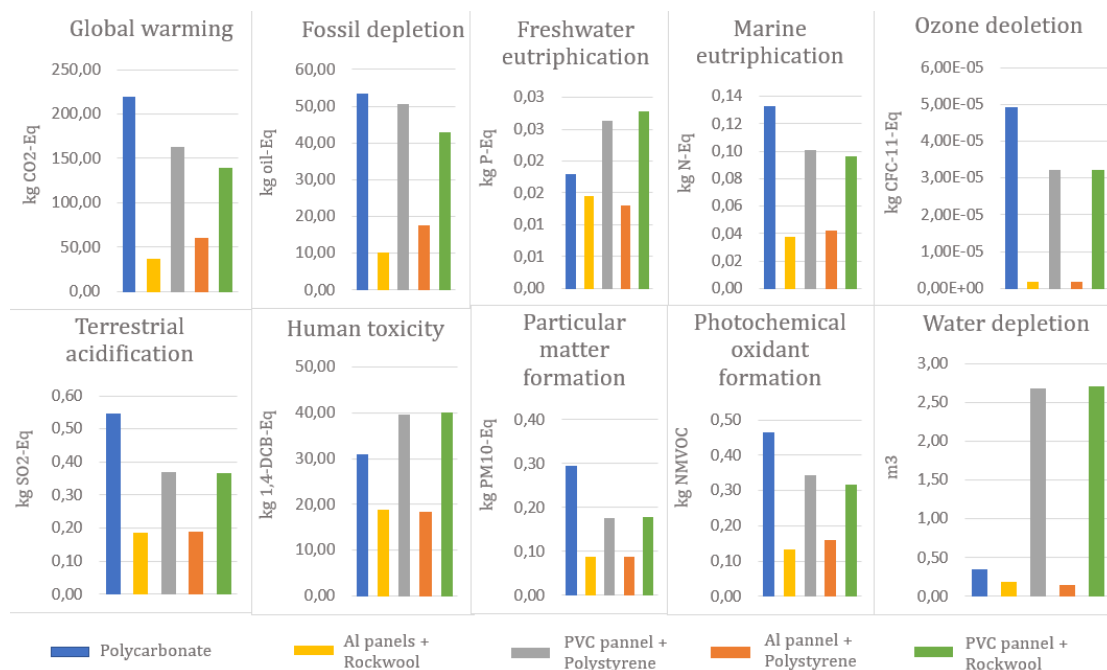


Figure 4.6 Environmental impacts of the noise barriers' whole cycle, second scenario, second cycle

In what follows, the Global warming category has been chosen to conduct a dominance analysis.

For the transparent (polycarbonate) noise barrier, the global warming potentials don't show a significant difference if it is recycled. As Figure 4.7 presents, the higher difference will be approximately 5% in the second cycle of usage, in other cycles it would be even less. The reason can be understood since polycarbonate is the main material in this type and its recycling rate is 2.5% (average recycling rate for construction plastics in Sweden). As it was mentioned before, the allocation method is based on Figure 4.1, therefore the disposal process of recycled material

will be allocated to the last (third) cycle in the second scenario. It explains the slight difference in the two scenarios' first cycles.

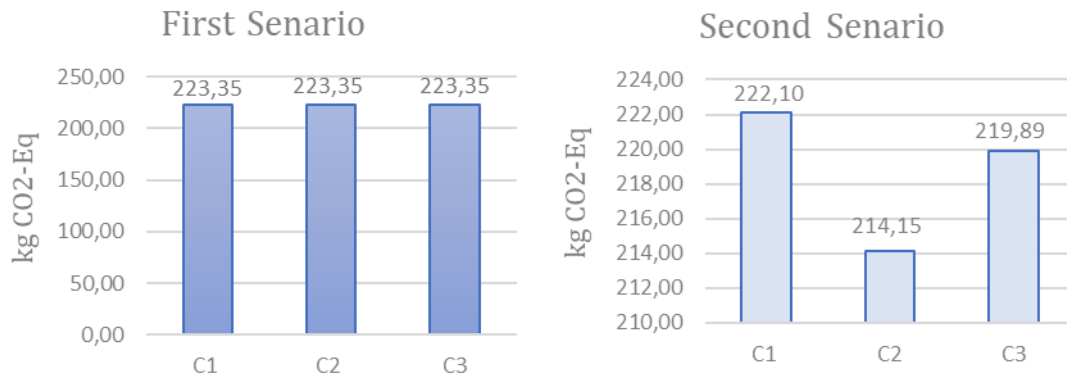


Figure 4.7 Polycarbonate noise barrier global warming potential (CO₂ kg eq.) in three life cycles (with or without recycling)

Because of the similarity of results, hot spot analysis will be conducted just for one scenario. As it is presented in Figure 4.8, material production has the highest impact (over 60%), which consists mainly of the market for polycarbonate production and extrusion (over 90%).

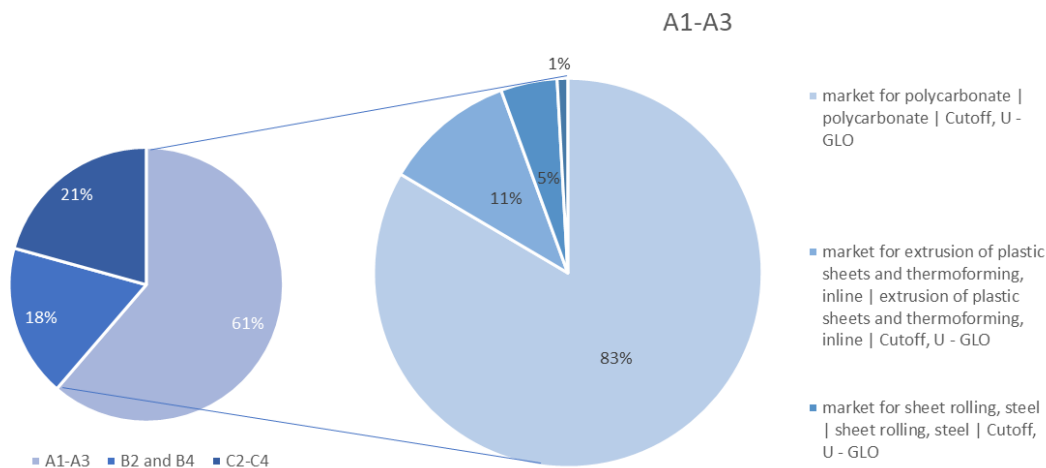


Figure 4.8 Polycarbonate noise barrier's hot spot analysis (first scenario)

For the SM noise barrier, two variations have been considered, aluminium panels filled with rock wool (Figure 4.7) and aluminium panels filled with polystyrene (Figure 4.10). The one filled with polystyrene has approximately 9% higher CO₂ emissions in the first scenario. The difference between the different cycles of the second scenario is slightly higher, as polystyrene has both a higher environmental impact and a lower recycling rate (2.5% in comparison to 25%).

However, in both cases, the CO₂ emissions have diminished noticeably approximately 85% (from 230 to 36 Kg CO₂) in the rock wool case and approximately 77% (from 252 to 60 Kg CO₂) in the polystyrene case in the second and third cycles of the second scenario. These reductions are due to the high rate of aluminium recycling which makes the Al+ Rock wool the greenest option in the second scenario among all barriers.

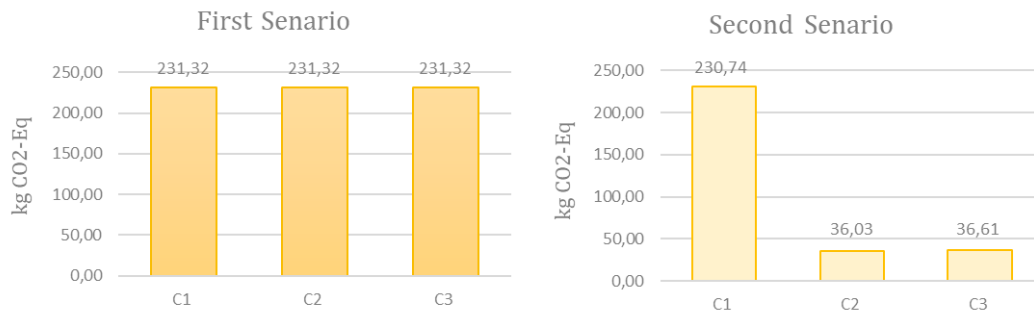


Figure 4.9 Alu+ Rock wool noise barrier global warming potential (CO₂ kg eq.) in three life cycles (with or without recycling)



Figure 4.10 Alu+ Polystyrene noise barrier global warming potential (CO₂ kg eq.) in three life cycles (with or without recycling)

By having a closer look at the Alu+ Rock wool barrier (Figure 4.11 and Figure 4.12), in both scenarios, material production has the highest impact, which mainly consists of the market for primary aluminium. Primary aluminium production is the main contributor to the first scenario (over 90%). However, in the second scenario in which aluminium has been 95% recycled, the environmental impact of primary aluminium production has reduced to 31% and the market for aluminium scrap preparation contributes to 9% of emissions which makes aluminium production still the dominance activity by contributing to 40% of emissions.

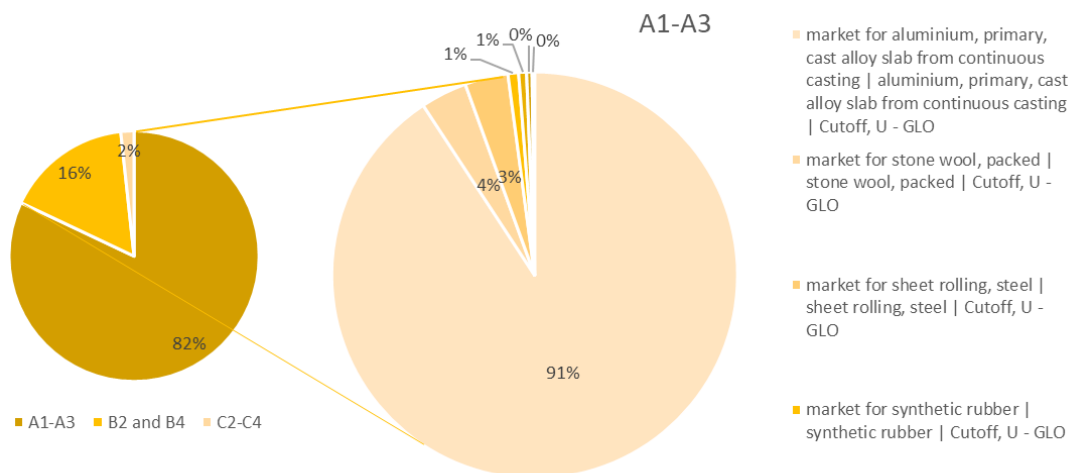


Figure 4.11 Alu+ Rock wool noise barrier's hot spot analysis (first scenario)

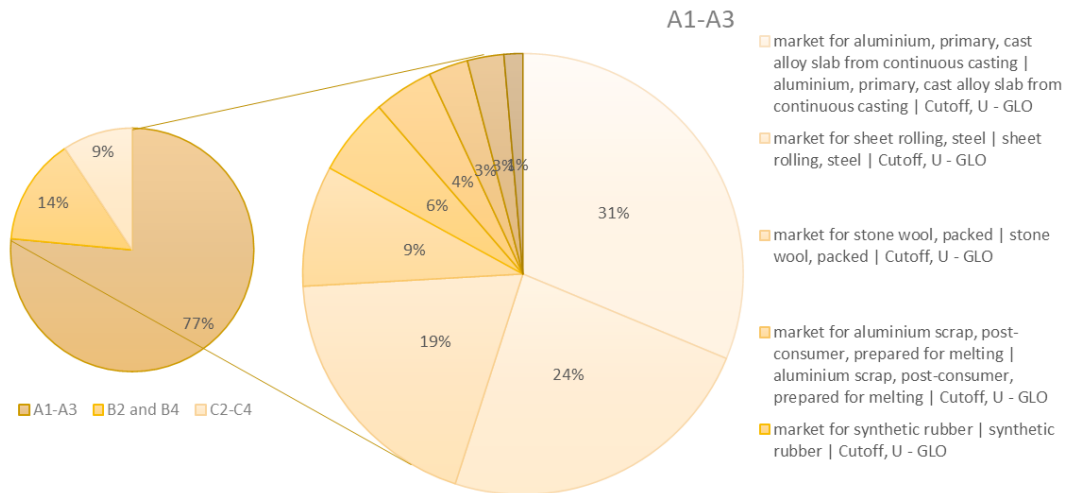


Figure 4.12 Alu+ Rock wool noise barrier's hot spot analysis (second scenario)

In the Al+ Polystyrene barrier case (Figure 4.13 and Figure 4.14), besides the high environmental impact of Aluminium production (which is the same as the previous case), polystyrene has a higher impact in comparison with rock wool which makes it the first contributor in the second scenario (37%) while aluminium is the second one.

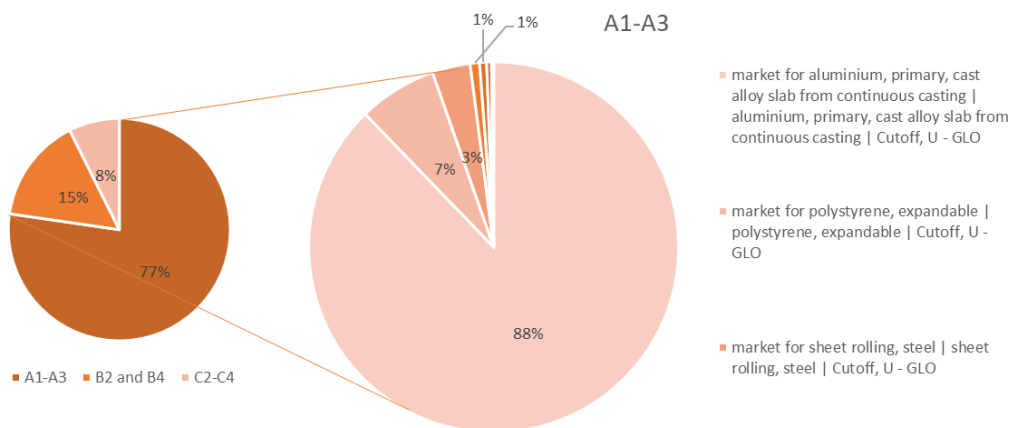


Figure 4.13 Alu+ polystyrene noise barrier's hot spot analysis (first scenario)

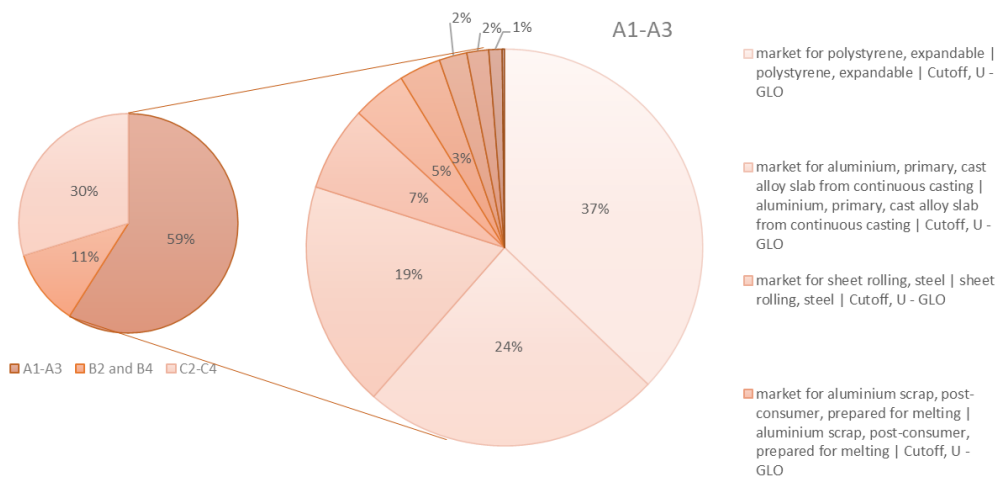


Figure 4.14 Alu+ Polystyrene noise barrier's hot spot analysis (second scenario)

For SP noise barriers also two options, either filled with rock wool or polystyrene, have been taken into account. PVC+ Rock wool has the lowest greenhouse gas emissions, in the first scenario. However, as it is presented in Figure 4.15 and Figure 4.16, the difference is not significant in both cases. Therefore, the hot spot analysis will be done for one scenario.

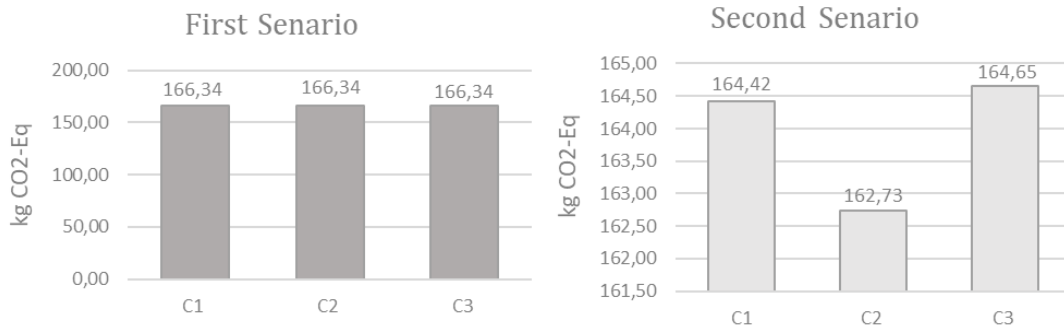


Figure 4.15 PVC+ Polystyrene noise barrier global warming potential (CO₂ kg eq.) in three life cycles (with or without recycling)

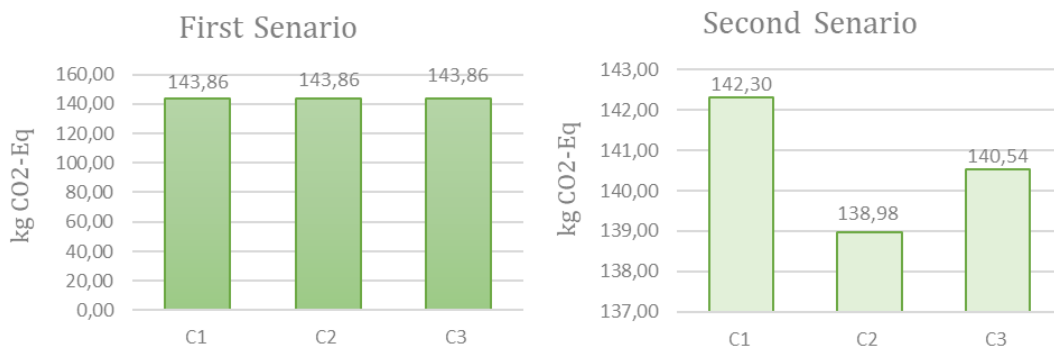


Figure 4.16 PVC+ Rock wool noise barrier global warming potential (CO₂ kg eq.) in three life cycles (with or without recycling)

Figure 4.17 and Figure 4.18 show the hot spot analysis for two variants of PVC barriers. For these barriers, both material production and end-of-life treatment have the highest impacts in the life cycle stages (each one is over 40%). In the production phase, the market for PVC, and in the end-of-life phase, treatment of PVC, has the highest contribution. As it was mentioned earlier, polystyrene has a higher environmental impact than rock wool in both the production and treatment stages.

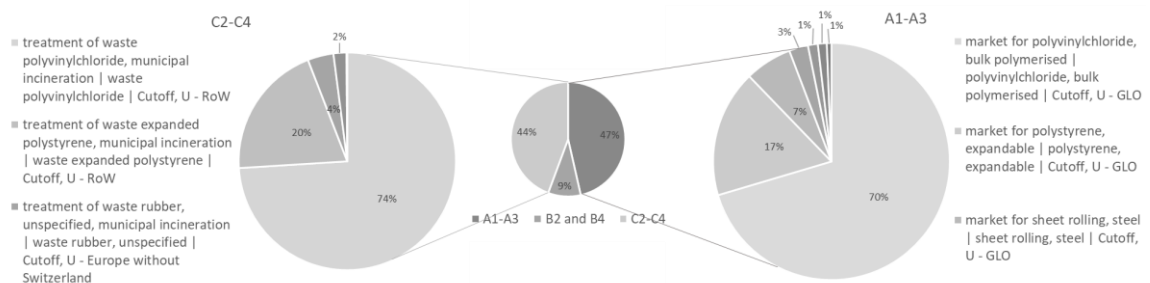


Figure 4.17 PVC+ polystyrene noise barrier hot spot analysis (first scenario)

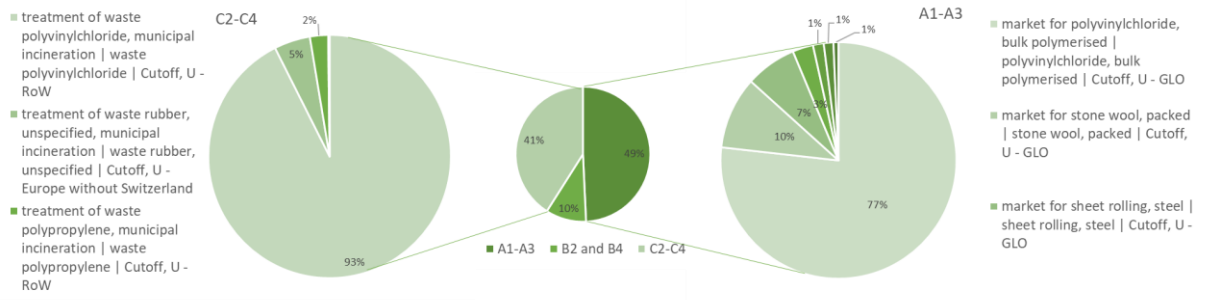


Figure 4.18 PVC+ Rock wool noise barrier hot spot analysis (first scenario)

5 Discussion

The result showed that the production phase (A₁-A₃) has the dominant global warming potential in the whole life cycle and for all barriers. Therefore, raw material extraction and processing have a significant impact on the environment, and environmental sustainability can be obviously improved by reducing primary material usage.

In the first scenario, SP barriers were the greenest options in most of the environmental impact categories while SM had almost the highest impact. However, due to the highest recyclable rate of aluminium in comparison to other materials, for the latter life cycles (in the second scenario) SM had the lowest environmental impact and was the most environmentally friendly option. As a result, besides material variation, considering the possible rate of recycling of each material in the industry is necessary for assessing the circular transition potential. Although SM showed different results in the first and second scenarios, the results for other barriers followed the same pattern in which ST had higher environmental impacts than SP (since both are plastic and have the same recycling rate which is not noticeable). Comparison between rock wool and polystyrene as the sound-absorbing materials showed rock wool could be the greener option due to both its higher rate of recycling and its lower environmental emissions during production and end-of-life treatment.

As was mentioned during the report, LCA just shows the potential impacts during the product life cycle based on geographical, technical, and other assumptions which might vary over time or different conditions. Therefore, in what follows, the parameters that might affect the result will be discussed.

The current thesis conducted the comparative life cycle assessment of several roadside noise barriers which highlighted the barriers and materials with dominant impacts. However, the focus of this assessment was only on the environmental impact (mostly global warming potential). If different sustainability indicators were chosen, it might change the result. For example, polycarbonate barriers showed the highest environmental impact than PVC panels, while polycarbonate is the only transparent barrier that does not block the view and it can be one of the social sustainability values. Another example is the difference between rock wool and polystyrene, sound absorption materials in PVC/aluminium panels. Polystyrene showed higher impact potential than rock wool; However, the technical function of them have not been considered, and it is possible that the greener one does not have the same acoustic properties.

The output of this research applies in Europe (since barely country-specific data has been used). To have a more realistic view of barriers impact, the foundation should also be included. As the foundation depends on the soil characteristics, the result might not be the same for all countries. Modules A₄ and A₅ (transportation and installation) have been excluded from this research, but by considering the specific location of the barriers, these two modules can be included to make the result more complete.

The barriers lifetime was expected to be 50 years. This assumption was based on one of the manufacturers' claims (Hammerglass), while the product guarantee period is 10 years for that product. Therefore, more investigation regarding the actual lifetime of different barriers might be needed.

There is not any major gap in data gathering. The generic database (ecoinvent) has been used while collecting first-hand data (from the manufacturer) will make the result closer to reality.

The recycling rate of all kinds of plastics has been considered 2.5%, as it is the average plastic recycling rate for the construction sector in Sweden. Plastic collecting and recycling are possible for specific products under specific conditions. It might occur in different companies based on the plastic fractions and recycling techniques that each company suggests. Therefore, it is important to form a direct dialogue with the respective company and the recycler who receives the material in the final stage. Plastic recycling is rarely possible if a plastic product is a mixture of products that contain different variants of plastics. As a result, the actual rate of recycling for each one might be higher or lower than 2.5%. It also should be mentioned that based on Hammerglass manufacturer and their end-of-life scenario in EPD, recycled polycarbonate and other clear materials are not qualified to be used again in European countries. Therefore, they will be transported to other countries, in this case, China, for the recycling process. As a result, it will not be a circular process, but downcycling. However, in this research, it is assumed that recycled products will be used in European countries to see how changing the scenario will affect the environmental impacts.

Considered aluminium recycling rate was based on the aluminium profile EPD, 95% of aluminium is recycled and the rest is landfilled. Nevertheless, the reference for that EPD was the European Aluminium Association, and it considered all kinds of aluminium products (like food packaging and so on). Therefore, for construction product, landfill does not seem reasonable, and the recycling rate must be higher.

Based on the rock wool manufacturer's sustainability report, the recycled content of their product is 25%. While it was not mentioned what percentage of this amount results from closed-looped recycling since there is also downcycling and upcycling of the material to and from other industries. However, in the cut-off allocation system, no raw material contribution will be considered after the first cycle of use. Therefore, there will not be a huge difference in the results if the materials are closed-looped recycled or not. And it was assumed that all are recycled within the same industry.

There is not any major gap or inconsistency in the report. However, all the mentioned points in this part express the possibilities for improvement and research or the areas of uncertainty and the reason behind it.

Besides comparing the environmental impact of different noise barriers and detecting hot spots modules/activities for further improvement, this report aimed to explore the possibility of linear to circular transition by searching for the possible recycling rates of the used materials and comparing the results. These investigations could be helpful for PROCEEDR tool development and on a larger scale, policymakers, and manufacturers.

6 Conclusion

Finding alternatives to diminish the environmental impacts of the transportation infrastructure has gained interest among decision-makers. Therefore, NRAs have run a project, PROCEEDR, intending to develop a software tool that assists them in finding a solution to facilitate the circular transition in the field of roadside noise and safety barriers.

This thesis intended to do a comparative life cycle assessment of the roadside noise barriers for the whole life cycle. The assessment has been done based on two scenarios. The first scenario was linear in which all virgin materials will be used, and then disposed of at the end of life. While the second scenario considered the recyclable rate of materials to be treated to be used for the next life cycles. The overall evaluation has been done based on 10 environmental indicators but with a focus on global warming potential.

The presented results indicate that in most cases, material production is the significantly highest contributor, and some factors can alter these contributions. One of them is using various materials with the same functions. Therefore, different panels, consisting of aluminium, polycarbonate, and PVC have been analysed with rock wool or polystyrene as the alternative sound absorption materials. For example, the result shows that aluminium has the highest global warming potential and PVC has the lowest in the first cycle of use. However, due to the higher recycling rate of aluminium (95% in comparison to 2.5 which is the recycling rate of plastic), it is the greenest option in the latter cycle. Therefore, the recycling rate of each material is the other important factor that must be considered to find out the possibility and potential of the improvement and circular transition.

The results of LCA are dependent on the completeness and accuracy of the data. In this research, several assumptions regarding material processes, treatment, and recycling rates have been made. Assumptions are an integral part of the LCA, however, using first-hand data (from the manufacturer) would lead to more accurate results.

The outcome of this research can be used to facilitate the PROCEEDR project tool development or for the decision maker and manufacturers to compare different options and detect improvement potentials. Although these results pinpoint the most environmentally friendly options, adding other indicators (such as economic and social) would make the overall sustainability evaluation possible.

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8 Appendix A – Modelled inventory data

Following tables present the quantity, ecoinvent material taken and provider, and the taken assumptions for each components/material of the selected noise barriers.

Table 8.1 Steel post + Polycarbonate noise barrier inventory data

Stages	Material	Ecoinvent material taken	Provider	Proxy taken/Assumption	Amounts	Unit
A1-A3	PC					
	Polycarbonate	Polycarbonate	market for polycarbonate polycarbonate Cutoff, U - GLO		14,44	kg
	Extruded Polycarbonate	market for extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		14,44	kg
	Steel Post					
	Rolling, forming	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		17,82	kg
	Hot-dip galvanized steel	zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. zinc coat, pieces instead of galvanized 2. Steel Density assumed 7850 kg/m ³ 3. The steel thickness is assumed 1 cm	0,23	m ²
	Other components					
Rubber	synthetic rubber production synthetic rubber Cutoff, U	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,36	Kg	

	Plastic	synthetic rubber production synthetic rubber Cutoff, U	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,004	Kg
B2 and B4	Cleaning					
	Water usage (per m ² each time)	tap water	market for tap water tap water Cutoff, U - Europe without Switzerland	10 ml water per square meter for cleaning	0,01	kg
	Mild household detergent (per m ² each time)	cleaning consumables, without water, in 13.6% solution state	market for cleaning consumables, without water, in 13.6% solution state cleaning consumables, without water, in 13.6% solution state Cutoff, U - GLO	detergent to water proportion: 13.6/100 water	0,00136	kg
	Module replacement					
	Polycarbonate	Polycarbonate	market for polycarbonate polycarbonate Cutoff, U - GLO	10% of modules each 10 years	14,44*3*0,1	kg
	Extruded Polycarbonate	market for extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO	10% of modules each 10 years	14,44*3*0,1	kg
	Rolling, forming	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO	10% of modules each 25 years	17,82*1*0,1	kg
	Hot-dip galvanized steel	zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	10% of modules each 25 years	1,51*1*0,1	m ²

	Rubber	synthetic rubber production synthetic rubber Cutoff, U	market for synthetic rubber synthetic rubber Cutoff, U - GLO	10% of modules each 10 years	0,36*3*0,1	Kg
	Plastic	synthetic rubber production synthetic rubber Cutoff, U	market for synthetic rubber synthetic rubber Cutoff, U - GLO	10% of modules each 10 years	0,004*3*0,1	Kg
C2-C4	Polycarbonate	waste plastic, mixture	treatment of waste plastic, mixture, municipal incineration waste plastic, mixture Cutoff, U - RoW		18,78	kg
	Rubber	waste rubber, unspecified	treatment of waste rubber, unspecified, municipal incineration waste rubber, unspecified Cutoff, U - Europe without Switzerland		0,469	kg
	Steel	scrap steel	treatment of scrap steel, inert material landfill scrap steel Cutoff, U - Europe without Switzerland		17,97	kg
A1-A3 and B4 (for second and third cycles)	Polycarbonate	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg
	Rubber	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg

Table 8.2 Steel post + Aluminium panel filled with Rock wool noise barrier inventory data

Stages	Material (Description)	Ecoinvent material taken	Provider	Proxy /Assumption taken	Amounts	Unit
A1-A3	Steel Post					
	HEB 160 steel profile	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		14,91	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,22	m ²
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		3,30	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,01	m ²
	Aluminium Alloy					
	Cassette aluminium alloy 500 x 2950 x 1,5 mm	aluminium, primary, cast alloy slab	market for aluminium, primary, cast alloy slab from continuous casting aluminium, primary, cast alloy slab from continuous casting Cutoff, U - GLO		9,04	kg
	Rock wool					
	Rock wool panel 2950 x 495 x 60 mm density 90 kg/m3	stone wool, packed	market for stone wool, packed stone wool, packed Cutoff, U - GLO		5,25	kg
	Other components					
End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,37	kg	

		extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,37	kg
	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,60	kg
B2 and B4	Cleaning					
	Water usage (per m2 each time)	tap water	market for tap water tap water Cutoff, U - Europe without Switzerland	10 ml water per square meter for cleaning	0,01	kg
	Mild household detergent (per m2 each time)	cleaning consumables, without water, in 13.6% solution state	market for cleaning consumables, without water, in 13.6% solution state cleaning consumables, without water, in 13.6% solution state Cutoff, U - GLO	detergent to water proportion: 13.6/100 water	0,00136	kg
	Module replacement					
	HEB 160 steel profile	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO	10% of modules each 25 years	14,91*1*0,1	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	10% of modules each 25 years	0,22*1*0,1	m ²
Base plate 0,4*0,4*0,03	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO	10% of modules each 25 years	3,3*1*0,1	kg	

		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,1*1*0,1	m ²
	Cassette aluminium alloy 500 x 2950 x 1,5 mm	aluminium, primary, cast alloy slab	market for aluminium, primary, cast alloy slab from continuous casting aluminium, primary, cast alloy slab from continuous casting Cutoff, U - GLO		9,04*2*0,1	kg
	Rock wool panel 2950 x 495 x 60 mm density 90 kg/m3	stone wool, packed	market for stone wool, packed stone wool, packed Cutoff, U - GLO		5,25*2*0,1	kg
	End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,37*2*0,1	kg
		extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,37*2*0,1	kg
	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,6*2*0,1	kg
C2-C4	Steel	scrap steel	treatment of scrap steel, inert material landfill scrap steel Cutoff, U - Europe without Switzerland		20,03	kg

	Aluminium	waste aluminium	treatment of waste aluminium, sanitary landfill waste aluminium Cutoff, U - RoW		10,85	kg
	Rock wool	waste mineral wool, for final disposal	treatment of waste mineral wool, inert material landfill waste mineral wool, for final disposal Cutoff, U - Europe without Switzerland		6,30	kg
	Polypropylene	waste polypropylene	treatment of waste polypropylene, municipal incineration waste polypropylene Cutoff, U - RoW		0,44	kg
	Rubber	waste rubber, unspecified	treatment of waste rubber, unspecified, municipal incineration waste rubber, unspecified Cutoff, U - Europe without Switzerland		0,72	kg
A1-A3 and B4 (recycled materials for Second and third cycles)	Aluminium	aluminium scrap, post-consumer, prepared for melting	market for aluminium scrap, post-consumer, prepared for melting aluminium scrap, post-consumer, prepared for melting Cutoff, U - GLO		95% (5 % is virgin material)	kg
		(Furnace energy usage) electricity, medium voltage	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE	For 95% (recycled material)		MJ

	Rock wool	electricity, medium voltage	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE	For 25% (recycled material)		KJ
	Polypropylene	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg
	Rubber	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg

Table 8.3 Steel post + PVC panel filled with Polystyrene noise barrier inventory data

Stages	Material (Description)	Ecoinvent material taken	Provider	Proxy /Assumption taken	Amounts	Unit
A1-A3	Steel Post					
	HEB 160 steel profile	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		11,36	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,17	m ²
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		2,51	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Steel Density assumed 7850 kg/m ³	0,01	m ²
	Recycled PVC					
	Cassette PVC 415 x 2950 x 3 mm	polyvinylchloride, bulk polymerised	market for polyvinylchloride, bulk polymerised polyvinylchloride, bulk polymerised Cutoff, U - GLO		21,63	kg
	Polystyrene foam					
	polystyrene foam panel 2950 x 395 x 80 mm	polystyrene, expandable	market for polystyrene, expandable polystyrene, expandable Cutoff, U - GLO		3,88	kg
	Other components					
End cap elements polypropylene	polypropylene, granulate	1.market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,47	kg	

		extrusion of plastic sheets and thermoforming, inline	2.market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,47	kg
	side gasket TPE rubber type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,75	kg
B2 and B4	Cleaning					
	Water usage (per m ² each time)	tap water	market for tap water tap water Cutoff, U - Europe without Switzerland	10 ml water per square meter for cleaning	0,01	kg
	Mild household detergent (per m ² each time)	cleaning consumables, without water, in 13.6% solution state	market for cleaning consumables, without water, in 13.6% solution state cleaning consumables, without water, in 13.6% solution state Cutoff, U - GLO	detergent to water proportion : 13.6/100 water	0,00136	kg
	Module replacement					
	HEB 160 steel profile	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		11,36*1*0,1	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,17*1*0,1	m ²
Base plate 0,4*0,4*0,03	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		2,51*1*0,1	kg	

		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,01*1*0,1	m ²
	Cassette PVC 415 x 2950 x 3 mm	polyvinylchloride, bulk polymerised	market for polyvinylchloride, bulk polymerised polyvinylchloride, bulk polymerised Cutoff, U - GLO		15,62*2*0,1	kg
	polystyrene foam panel 2950 x 395 x 80 mm	polystyrene, expandable	market for polystyrene, expandable polystyrene, expandable Cutoff, U - GLO		3,88*2*0,1	kg
	End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,47*2*0,1	kg
		extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,47*2*0,1	kg
	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,75*2*0,1	kg
C2-C4	Steel	scrap steel	treatment of scrap steel, inert material landfill scrap steel Cutoff, U - Europe without Switzerland		15,26	kg

	PVC	waste polyvinylchloride	treatment of waste polyvinylchloride, municipal incineration waste polyvinylchloride Cutoff, U - RoW		25,96	kg
	polystyrene foam	waste expanded polystyrene	treatment of waste expanded polystyrene, municipal incineration waste expanded polystyrene Cutoff, U - RoW		4,66	kg
	Polypropylene	waste polypropylene	treatment of waste polypropylene, municipal incineration waste polypropylene Cutoff, U - RoW		0,56	kg
	Rubber	waste rubber, unspecified	treatment of waste rubber, unspecified, municipal incineration waste rubber, unspecified Cutoff, U - Europe without Switzerland		0,90	kg
A1-A3 and B4 (recycled materials for Second and third cycles)	PVC	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5% is virgin material)	kg
	polystyrene foam	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5% is virgin material)	kg

	Polypropylene	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg
	Rubber	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN		2,5% (97,5 % is virgin material)	kg

Table 8.4 Steel post + Aluminium panel filled with Polystyrene noise barrier inventory data

Stages	Material (Description)	Ecoinvent material taken	Provider	Proxy /Assumption taken	Amounts	Unit
A1-A3	Steel Post					
	HEB 160 steel profile	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		14,91	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,22	m ²
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		3,30	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Steel Density assumed 7850 kg/m ³	0,01	m ²
	Aluminium Alloy					
	Cassette aluminium alloy 500 x 2950 x 1,5 mm	aluminium, primary, cast alloy slab	market for aluminium, primary, cast alloy slab from continuous casting aluminium, primary, cast alloy slab from continuous casting Cutoff, U - GLO		9,04	kg
	Polystyrene					
	polystyrene foam panel 2950 x 495 x 80 mm	polystyrene, expandable	market for polystyrene, expandable polystyrene, expandable Cutoff, U - GLO		3,89	kg
	Other components					

	End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,37	kg
		extrusion of plastic sheets and thermoforming , inline	market for extrusion of plastic sheets and thermoforming , inline extrusion of plastic sheets and thermoforming , inline Cutoff, U - GLO		0,37	kg
	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,60	kg
B2 and B4	Cleaning					
	Water usage (per m ² each time)	tap water	market for tap water tap water Cutoff, U - Europe without Switzerland	10 ml water per square meter for cleaning	0,01	kg
	Mild household detergent (per m ² each time)	cleaning consumables, without water, in 13.6% solution state	market for cleaning consumables, without water, in 13.6% solution state cleaning consumables, without water, in 13.6% solution state Cutoff, U - GLO	detergent to water proportion: 13.6/100 water	0,00136	kg
	Module replacement					
	HEB 160 steel profile	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		14,91*1*0,1	kg

		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,22*1*0,1	m2
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for sheet rolling, steel sheet rolling, steel Cutoff, U - GLO		3,3*1*0,1	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,01*1*0,1	m2
	Cassette aluminium alloy 500 x 2950 x 1,5 mm	aluminium, primary, cast alloy slab	market for aluminium, primary, cast alloy slab from continuous casting aluminium, primary, cast alloy slab from continuous casting Cutoff, U - GLO		9,04*2*0,1	kg
	polystyrene foam panel 2950 x 495 x 80 mm	polystyrene, expandable	market for polystyrene, expandable polystyrene, expandable Cutoff, U - GLO		3,89*2*0,1	kg
	End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,37*2*0,1	kg
		extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,37*2*0,1	kg

	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,6*2*0,1	kg
C2-C4	Steel	scrap steel	treatment of scrap steel, inert material landfill scrap steel Cutoff, U - Europe without Switzerland		20,03	kg
	Aluminium	waste aluminium	treatment of waste aluminium, sanitary landfill waste aluminium Cutoff, U - RoW		10,85	kg
	polystyrene foam	waste expanded polystyrene	treatment of waste expanded polystyrene, municipal incineration waste expanded polystyrene Cutoff, U - RoW		4,67	kg
	Polypropylene	waste polypropylene	treatment of waste polypropylene, municipal incineration waste polypropylene Cutoff, U - RoW		0,44	kg
	Rubber	waste rubber, unspecified	treatment of waste rubber, unspecified, municipal incineration waste rubber, unspecified Cutoff, U - Europe without Switzerland		0,72	kg
	A1-A3 and B4 (recycled materials for Second and	Aluminium	aluminium scrap, post- consumer, prepared for melting	market for aluminium scrap, post- consumer, prepared for melting aluminium scrap, post- consumer,		95% (5 % is virgin material)

third cycles)			prepared for melting Cutoff, U - GLO			
		(Furnace energy usage) electricity, medium voltage	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE	For 95%recycled material	0,95*9,04*6,07	MJ
	polystyrene foam	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN	2.5% recycled	2,5% (97,5% is virgin material)	kg
	Polypropylene	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN	2.5% recycled	2,5% (97,5% is virgin material)	kg
	Rubber	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN	2.5% recycled	2,5% (97,5% is virgin material)	kg

Table 8.5 Steel post + PVC panel filled with Rock wool noise barrier inventory data

Stages	Material (Description)	Ecoinvent material taken	Provider	Proxy /Assumption taken	Amounts	Unit
A1-A3	Steel Post					
	HEB 160 steel profile	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		11,36	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,17	m2
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		2,51	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,01	m2
	Recycled PVC					
	Cassette PVC 415 x 2950 x 3 mm	polyvinylchloride, bulk polymerised	market for polyvinylchloride, bulk polymerised polyvinylchloride, bulk polymerised Cutoff, U - GLO		21,63	kg
	Rock wool					
	Rock wool panel 2950 x 495 x 60 mm density 90 kg/m3	stone wool, packed	market for stone wool, packed stone wool, packed Cutoff, U - GLO		5,24	kg
	Other components					
End cap elements polypropilene	polypropylene, granulate	1.market for polypropylene, granulate polypropylene		0,47	kg	

			ne, granulate Cutoff, U - GLO			
		extrusion of plastic sheets and thermoforming , inline	2.market for extrusion of plastic sheets and thermoform ing, inline extrusion of plastic sheets and thermoform ing, inline Cutoff, U - GLO		0,47	kg
	side gasket TPE rubber type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,75	kg
B2 and B4	Cleaning					
	Water usage (per m ² each time)	tap water	market for tap water tap water Cutoff, U - Europe without Switzerland	10 ml water per square meter for cleaning	0,01	kg
	Mild household detergent (per m2 each time)	cleaning consumables, without water, in 13.6% solution state	market for cleaning consumable s, without water, in 13.6% solution state cleaning consumable s, without water, in 13.6% solution state Cutoff, U - GLO	detergent to water proportion: 13.6/100 water	0,00136	kg
	Module replacement					
HEB 160 steel profile	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel		11,36*1*0,1	kg	

			Cutoff, U - GLO			
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Profile unit mass: 42.6 kg/m	0,17*1*0,1	m2
	Base plate 0,4*0,4*0,03	sheet rolling, steel	market for section bar rolling, steel section bar rolling, steel Cutoff, U - GLO		2,51*1*0,1	kg
		zinc coat, pieces	market for zinc coat, pieces zinc coat, pieces Cutoff, U - GLO	1. Zinc coat, pieces l instead of galvanized 2. Steel Density assumed 7850 kg/m3	0,01*1*0,1	m2
	Cassette PVC 415 x 2950 x 3 mm	polyvinylchloride, bulk polymerised	market for polyvinylchloride, bulk polymerised polyvinylchloride, bulk polymerised Cutoff, U - GLO		21,63*2*0,1	kg
	Rock wool panel 2950 x 495 x 60 mm density 90 kg/m3	stone wool, packed	market for stone wool, packed stone wool, packed Cutoff, U - GLO		5,24*2*0,1	kg
	End cap elements polypropylene	polypropylene, granulate	market for polypropylene, granulate polypropylene, granulate Cutoff, U - GLO		0,47*2*0,1	kg

		extrusion of plastic sheets and thermoforming, inline	market for extrusion of plastic sheets and thermoforming, inline extrusion of plastic sheets and thermoforming, inline Cutoff, U - GLO		0,47*2*0,1	kg
	Side gasket EPDM type	synthetic rubber	market for synthetic rubber synthetic rubber Cutoff, U - GLO		0,75*2*0,1	kg
C2-C4	Steel	scrap steel	treatment of scrap steel, inert material landfill scrap steel Cutoff, U - Europe without Switzerland		15,26	kg
	PVC	waste polyvinylchloride	treatment of waste polyvinylchloride, municipal incineration waste polyvinylchloride Cutoff, U - RoW		25,96	kg
	Rock wool	waste mineral wool, for final disposal	treatment of waste mineral wool, inert material landfill waste mineral wool, for final disposal Cutoff, U - Europe without Switzerland		6,29	kg

	Polypropylene	waste polypropylene	treatment of waste polypropylene, municipal incineration waste polypropylene Cutoff, U - RoW		0,56	kg
	Rubber	waste rubber, unspecified	treatment of waste rubber, unspecified, municipal incineration waste rubber, unspecified Cutoff, U - Europe without Switzerland		0,90	kg
A1-A3 and B4 (recycled materials for Second and third cycles)	PVC	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN	2.5% recycled	2,5% (97,5% is virgin material)	kg
	Rock wool	electricity, medium voltage	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SE		25% (75% is virgin material)	kg
	Polypropylene	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled plastic granulate, unspecified, recycled Cutoff, U - IN	2.5% recycled	2,5% (97,5% is virgin material)	kg
	Rubber	plastic granulate, unspecified, recycled	market for plastic granulate, unspecified, recycled	2.5% recycled	2,5% (97,5% is virgin material)	kg

			plastic granulate, unspecified, recycled Cutoff, U - IN			
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9 Appendix B – Environmental impacts

The following tables show the whole life cycle environmental impact based on 10 different categories, calculated by ReCiPe midpoint (h) and for two different scenarios (with or without recycling).

Table 9.1 Noise barriers' whole life cycle environmental impacts (first scenario)

Impact Categories	Unit	Polycarbonate	Al + Rock wool	PVC + Polystyrene	Al + Polystyrene	PVC + Rock wool
GWP	kg CO2-Eq	223,35	231,32	166,34	253,80	143,86
FDP	kg oil-Eq	54,38	50,37	51,51	68,49	44,41
FEP	kg P-Eq	0,02	0,13	0,03	0,13	0,03
MEP	kg N-Eq	0,13	0,28	0,10	0,29	0,10
ODP	kg CFC-11-Eq	5,03E-05	7,08E-06	3,30E-05	6,97E-06	3,31E-05
TAP	kg SO2-Eq	0,56	1,64	0,37	1,63	0,38
HTP	kg 1,4-DCB-Eq	31,15	131,62	40,18	130,44	41,25
PMFP	kg PM10-Eq	0,30	0,69	0,18	0,69	0,18
POFP	kg NMVOC	0,47	0,87	0,35	0,89	0,33
WDP	m3	0,35	0,78	2,74	0,73	2,78

Table 9.2 Noise barriers' whole life cycle environmental impacts (second scenario, second cycle)

Impact Categories	Unit	Polycarbonate	Al + Rock wool	PVC + Polystyrene	Al + Polystyrene	PVC + Rock wool
GWP	kg CO2-Eq	218,65	36,03	162,73	59,90	138,98
FDP	kg oil-Eq	53,22	9,94	50,34	17,49	42,85
FEP	kg P-Eq	0,02	0,01	0,03	0,01	0,03
MEP	kg N-Eq	0,13	0,04	0,10	0,04	0,10
ODP	kg CFC-11-Eq	4,91E-05	1,76E-06	3,22E-05	1,76E-06	3,22E-05
TAP	kg SO2-Eq	0,55	0,19	0,37	0,19	0,36
HTP	kg 1,4-DCB-Eq	30,82	18,81	39,50	18,29	40,04
PMFP	kg PM10-Eq	0,29	0,09	0,17	0,09	0,18
POFP	kg NMVOC	0,46	0,13	0,34	0,16	0,32
WDP	m3	0,34	0,18	2,67	0,15	2,71

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