The environmental performance of the new circular mattress
A life cycle study

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Preface

This thesis is the result of my master graduation project for the Production & Logistics Management specialization of the Industrial Engineering and Management Master's degree at the University of Twente. In the last 25 weeks, I conducted a research for Royal Auping in Deventer, that gave me the opportunity to deep dive into the complex world of sustainability and circularity. All the research methods and their results are collected and merged into this Master's thesis, which I proudly present. However, this result would have never been possible without the support and feedback of several people, who I hereby would like to thank.

First, I would like to thank my supervisors Devrim Yazan and Eduardo Lalla-Ruiz for their support, valuable input and feedback throughout my thesis. Then, I would like to bring a special word of thanks to Dr. J.G. Vogtländer from the T.U. Delft, for dedicating his time to share some of his great LCA knowledge with me.

Then, I would like to thank my supervisor at Auping, G. Doorlag, for helping me keeping this project on track and his usefull tips and information. Furthermore, I would like to thank all other collegues at Auping, that always were willing to help me finding all required information.

I am also very thankful for my family and friends. My girlfriend Marjolein and my (step)parents, for their continuous support during my study and this graduation thesis. My sister Sofie, for her tremendous help at structurizing the work, and valuable advices.

Lastly, I would like to end with a quote, that in my opinion, should be supported by all future engineers.

"Waste is a design flaw"

Kate Kreba

Management summary

In this report, we present the first Life Cycle Analysis, in which the carbon footprint of a circular mattress is compared with a conventional one. The report contains a research project at Royal Auping B.V. that aimed to investigate spectrum of environmental impact tools and analyse the impact of two products through one specifically selected method.

In order to maintain a world in which people can live in a healthy and comfortable manner, organizations need to shift from linear to circular business models. Linear and circular refer to the end-of-life of products, that involves a loss of structure and energy (linear) or a recurrent material flow and limited use of virgin materials (circular). The Dutch Government set the ambitious goal to become a complete circular society in 2050. Royal Auping wants to take an inspiring and pioneering role, aiming to be circular 20 years earlier, by 2030.

A major milestone on Auping's path to circularity is the new circular mattress concept, Evolve. Circularity is hereby achieved by its closed loop recycling system: material of former mattresses is recycled into new mattress, without loss of quality. This can be achieved by two principles: composition (PET and steel) and modularity (easy disassembly adhesive). Since closed loop recycling is still in a pioneering phase for textiles, a solid proof of concept is lacking. As a consequence, Auping was in need of a quantitative tool to measure the environmental impact of this new concept, both to validate the chosen path, and to consolidate its domain knowledge. This leads us to the following research aim:

"Quantify the environmental impact of the circular mattress Evolve, by use of a relevant and reliable tool"

By executing an extensive literature study, we decided to measure the impact of the mattress by a Life Cycle Analysis (LCA). Complementary, a framework that organizes the environmental burdens, ReCiPi, is applied, selecting global warming as impact indicator. Hereby, the products' global warming potential are indicated by its carbon footprint; the emission of greenhouse gasses to the atmosphere expressed in kg CO2 equivalents. The LCA consist of four phases:

1. *Definition of the goal and Scope*: In this phase, the research aim is defined and system boundaries, i.e. the in- and exclusions, are set.
2. *Inventory analysis:* In the Life Cycle Inventory (LCI) phase, representative data is collected to model the life cycles.
3. *Impact assessment*: In this phase, all collected data is transformed into kg CO2 equivalents by certain characterization factors. In this LCA defined by the ReCiPe framework.
4. *Interpretation*: Subsequently the results are analysed and conclusions are drawn. Importantly, the system boundaries should always be considered when comparing outcomes with others.

Table 1 gives an overview of the LCA specific characteristics for this thesis.

LCA case specific characteristics				
Impact indicator	System bounds	Functional unit	Cut-off criteria	Tool
Global warming impact	Vivo: **Cradle to grave** (Raw material- incineration/ downcycling) Evolve: **Cradle to cradle** (from raw material to raw material)	One mattress 90 x 210 use of ten years.	1% lower bound weight 5% lower bound carbon footprint	Excel based program, organizing all processes parameters, calculations and assumptions

Table 1. Main structural decisions LCA

In order to fulfil the LCA, the following decisions were made and activities were performed for the purpose of an efficiently and effectively execution:

1. *Selection of a framework to ensure representativeness and wide acceptance of the results*: The ISO 14067 is used as main study structure here. By these guidelines, the representativeness and completeness of a LCA can be enhanced.
2. *The development of a sophisticated tool to organize all data*. Instead of using (costly) dedicated software such as SimaPro and Gabi, a customized excel tools is created, that enables advanced analysis in a consistent and transparent manner. This tool fungates as database, impact calculation framework and uncertainty analysis tool. To calculate the impact of every process, material flows and energy flows were transformed into kg CO_2e,
3. *Reliable and representative data sources.* Both primary data and secondary data are used, i.e. respectively measurements of the specific location under study or standard data. A hierarchical decision flowchart is used, to ensure that the best data available is used. The primary data for this thesis is based on external and internal measurements. Specifically, for the modelling of transportation the distance, transport efficiencies are gathered by internal information and approximating techniques. The secondary data is sourced mainly from the 'Idemat2020 database'.
4. *A qualitative or quantitative method to indicate uncertainties*. As most data in this study is based on single measurements, the uncertainty of the data cannot be based on statistical data. By a pedigree approach and Monte Carlo simulations, all inventory data is first evaluated on representativeness and reliability. Then, an indication of the uncertainty could be provided.

Based on the executed LCA study the following conclusions can be drawn, concerning the new Evolve innovation from Auping:

- The closed loop recycling of PET for Evolve, has a carbon footprint reducing potential of 27 kg CO_2e, from which 19 kg saved on virgin material and 12 kg by prevented waste incineration.
- The recycling burden for Evolve is estimated at 4 kg CO_2e for recycling in The Netherlands, based on early tests. An extra 9 kg CO_2e (transport) is expected for recycling in Austria.
- The recycling rate, a measure for the recycled material share against the recycling waste, is estimated conservatively at 89%. Presumably, a higher rate can be obtained for a more customized and optimized recycling system.
- For a 75% re-use of the pocked springs, the carbon footprint saving potential is 14 kg CO_2e . Hereby, the processing burden for re-use (refurbishing) is not yet known, thus excluded.
- In comparison with the conventional mattress Vivo, a carbon footprint reduction of 53% is expected (in a range of 45% and 60%, considering the data uncertainty).
- The potential cost savings of the concept are: €8,- on Virgin PET, €20,- for virgin pocked springs (for 70% re-use) and €5,- for the avoided disposal gate-fee. Thus, if the additional costs for recycling and re-use are below €33,-, these measures will be economical beneficial as well.

For these reasons, the Evolve can be seen as improvement on the conventional mattresses from a global warming perspective. Furthermore, in the light of this thesis, we recommend Auping the following:

- Invest in a LCA software tool (SimaPro) and licenced database (Ecoinvent), for effective, well efficient LCA analyses with generally accepted results.
- If not, invest in a tool or system that give insights in the different material flows in the life cycle of products. By having a clear overview of the recyclability and magnitude of material flows, both the effectiveness and efficiency of the closed loop recycling system can be improved.

Definition	Explanation
Allocation (partitioning)	Allocation or partitioning is used to avoid dubble counting of envrionmental burdens: "Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14044).
Carbon footprint	Carbon footprint is a commonly used methodology in which the greenhouse gas emissions during the life cycle of a product can be measured in terms of their kg carbon dioxide equivalents (CO2e) (Vogtlander, 2015).
Components	All products that are directly bought by Auping for the production of the mattresses. Hereby, something is only considered a component if thee material ends up (partly) in the final mattress.
Cradle-to-gate	"An assessment that includes part of the product's life cycle, including material acquisition through the production of the studied product and excluding the use or end-of-life stages" (WRI and WBCSD 2010).
Cut-off criteria	"Specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study" (ISO 14040).
Direct resources	The resource of energy that is used in a factory in that specific form. *E.g.: a gas driven oven in a factory. Direct resource: gas*
Direct supplier	Organization that supplies components to Royal Auping. Hereby, there is a purchase agreement between Auping (as customer) and the supplier.
Indirect resources	The energy resources used to produce the direct resources used in the factory.
Life cycle assessment (LCA):	"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product (system) throughout its life cycle" (consequential LCA sd).
Life cycle inventory analysis (LCI):	"Phase of life cycle assessment involving the compilation and quantification of exchanges for a product throughout its life cycle" (consequential LCA sd).
Pedigree matrix	A semi-quantitative in which first scores are given for certain criteria. By specific conversion factors, from these quantitative uncertainty score is derived.
Product system	The part of a product's life cycle that is included in the system bounderies, set in the goal and scope phase.
Product version	The specific product from a product line, with specific, materials (fillings) and year of release. Minor updates of a certain product release lead to a different version
Sub-supplier	Organization that contributes to the supply of a component, but is not in direct contact with Royal Auping. This party can be seen as the supplier of a supplier.
Uncertainty	Quantitative definition: Measurement that characterizes the dispersion of values that could reasonably be attributed to a parameter (adapted from ISO 1995).
Unit process	The smallest portion of a product system for which data is collected (ISO 14067:2018).
Virgin material	That has not been previously used or consumed, or subjected to processing other than for its original production.

Glossary

Contents

1. Introduction

In the introduction, the following questions are being answered:

- Why is this research needed for Auping?
- What is the research goal?
- What research questions shall be answered?
- What is the framework of this thesis?

1.1 Introduction

The rate at which the earth's natural resources are consumed, is recognized being unsustainable for a very long time (Behrens et al. 2007), (Green 1894), (Malthus 1798). The amounts of materials extracted, harvested and consumed worldwide, has increased eight-fold since 1900 (OECD 2015). In order to feed and to enable future generations to live an healthy and comfortable life as well, this unacceptable pattern needs to be reversed. Furthermore, the increased material consumption has an additional effect: the release of unwanted by-products, Greenhouse gasses, GHGs. These gasses form a sort of impermeable membrane around the planet, that withhold heat radiation to flowing back to the atmosphere. As a consequence, the temperature on earth is increasing rapidly. According to the world's largest weather data archive NCDC, since 1880, the ten warmest years all took place after 1998 (NOAA 2020). Global warming has disastrous consequences for the planet and all living creatures, e.g. heat stress, spreading of diseases, extreme weather, ocean acidity, increased sea levels and many more (IPCC 2007). Therefore, in 2018 the intergovernmental Panel on Climate Change (IPCC), strongly recommended to control the increase in global temperature below 1.5 °C (relative to the year 1750), to avoid disastrous ecologic and economic effects (IPCC 2018).

To transform this problematic situation into a more sustainable one, action is needed on all levels of the society. The concept of sustainability is often understood by people, companies and governments. However, solely understanding the concept and urgency, will not solve this problematic situation. Therefore, constructive actions are required. Unfortunately, how to take action effectively, is often a big question mark (Baumann 2004). The Dutch government sees the circular economy as potential answer to this immense 21st century challenges (IenW 2016). According to the Ellen Macarthur foundation, one of the major protagonists of the circular movement, circularity can be defined as follows:

"The circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems."
(Ellen Macarthur Foundation 2020)

This circular society, shall be able to fulfil the human needs, without exhausting the planet on natural resources and affecting the environment in a disastrous way. However, according to the Circularity Gap Report, the global economy is only 9% circular today. The Netherlands performs significantly better than world average by 24.5%, but is still not approaching a fully circular, wasteless economy. (Circle Economy 2019). To change this, the Dutch government has the ambitious goals to become completely circular by 2050. To achieve this, the enormous yearly consumption of materials, minerals and fossil fuels of 221 million tonnes, should be reduced significantly (Circle Economy 2019). In order to contribute to this national objective, various initiatives are taken by governments agencies, companies and other organizations. An organization that have initiated an initiative is the Dutch bedding company Royal Aupings.

Royal Auping BV, founded in 1888, is a Dutch producer and supplier of consumer goods in the sleep sector, active in over 20 countries worldwide. Auping produces a great variety of sleeping products, comprising beds, mattresses and even sleeping robots. This manufacturer has a large production facility in Deventer, that includes a steel, wood and textile division. For mattresses, most of the components are manufactured externally, and then assembled and finished at Auping. The role of this bedding producer can thus also be defined as assembler, in the mattress production chain.

Every year, 40 million mattresses are discarded in Europe. Mattresses have a lifespan of more or less 10 years (Auping 2020), after which the materials are either burned, landfilled or (partially) used as base material for other type of products. The latter is rather an extension of the effective use of materials, than a long term solution; after this second use it cannot be used anymore. The current end-of-life of mattresses, incurs losses of useful materials and affects the environment by the release of carbon dioxide and other harmful by products. Auping introduced a new sustainable business model, anticipating on the increasing demand for more environmentally friendly solutions.

With the release of the mattress “Evolve”, Auping claims to be the first company worldwide that delivers a circular mattress product (Auping 2020). The new mattress, is completely designed to serve their circular ambition, which is realized by its modular design and its recyclable materials. Already in the early design phases, the objective was to design a mattress that is completely recyclable without loss of quality in terms of comfort, safety and hygiene. The production process for this new mattress is designed in the way that the material of former mattresses will be recycled and used as raw material for new exemplars. Again, without the degradation of the product quality. In 2030, Auping aims to have a complete circular product range (Auping 2020). In this first-mover role, Auping aughts to create a major change in the market and tries to actively motivate other parties to join this movement.

In the current phase of the development process of the new mattress Evolve, Auping is in the need of a quantitative underpinning of the assumed environmental benefits. To have a complete view of the impact of products, the complete life cycle should be evaluated. A life cycle can be defined as follows:

This thesis presents the Life Cycle Analysis response to the quantitative need of Auping for the Evolve mattress. To date, there is no available literature that evaluates the environmental impact of a circular mattress, neither there is relevant information for this form of recycling. As a result, this thesis will be the first environmental impact analysis openly available, comparing a circular mattress life cycle, with a conventional instance.

Life cycle:

“Consecutive and interlinked stages related to a product, from raw material acquisition or generation from natural resources, to end-of life treatment”.

(ISO 14067:2018 sd)

1.2 Product introduction: The Vivo and Evolve mattress

In this thesis, the potential benefit of the new circular mattress is approached. In order to achieve this, a comparison is made between the new mattress and a conventional exemplar. These are the conventional mattress "Vivo" and the circular mattress "Evolve".

Conventional refers hereby to the end-of-life path of this product, that results in a loss of materials. In The Netherlands, the conventional end-of-life path for disposed mattresses involves either incineration or recycling. For the latter, the recycled waste flow is (partly) used for other products such as furniture fillings or insulation foams. This phenomenon is often referred to as downcycling, in case the secondary product is considered to be of lower grade or value. After this secondary use, the material cannot be recycled again. Auping states that the new mattress is a better option for the environment, meeting the same high quality standards.

Thereafter, the lifecycle of the circular mattress "Evolve" is analysed. In contrast to the Vivo mattress, recycled material of the Evolve will serve as input for new mattresses, thus form a closed loop. The mattress contains a number of distinctive features. First of all, this mattress is only[1] composed of two material types: polyester and steel, that both possess good recycling properties. These are connected by a special thermoplastic adhesive, chosen to ease disassembly of the components. Further, in order to keep track of products in the market, a so called "mattress" passport is attached to all Evolve mattresses. This electronic chip serves two goals: to inform the consumer about the specific product (scannable by smartphone) and to inform the manufacturer the product characteristics when returned after disposal, to ensure a controlled material loop.

Evolve

- New circular product line
- 90 x 210 cm
- Bill of materials: 20 components
- Total weight +/- 19 kg
- Mattress passport
- Mattress- to-mattress recycling

VIVO

- The conventional product
- 90 x 210 cm
- Bill of materials: 48 components
- Total weight +/- 24.5 kg
- Downcycling

[1] A minor amount of melt fiber is used in the non-woven layers. that is another polyester variant (group: bico polyester)

1.3 Problem analysis

The introduction of the new circular mattress Evolve in May 2020, involved many changes for the involved stakeholders. Instead of the usage of only virgin material, a recurrent flow of recycled materials is added for the composing of the mattresses. In contrast to regular product releases, the circular business model requires a complete redesign of the supply chain and the end-of-life flows:

- New recycling processes are developed, to create "new" material from disposed mattresses.
- The collaboration between the manufacturer and suppliers changes: the manufacturer is now a reversed supplier of recycled material for the suppliers of the components.

As a consequence of being a 'first mover', information regarding supply chain dynamics of a circular business model in the bed sector are limited. Aupings knowledge about the performance of the intended circular supply chain, regarding greenhouse gas emissions, material use and costs, is limited and to a great extent based on qualitative assumptions. Until now, decisions for the new matrass were mainly based on the sustainable vision of Auping and the knowledge on a product design level. For the next phase of the development process Auping asks for quantitative and objective research to be able to provide internal and external stakeholders a better indication of the potential of their circular mattress concept. Moreover, this research can be used to inspire other companies to follow a more circular path for its product base.

Firstly, this new quantitative knowledge can support future decision making on a strategic, tactical and operational level. On a strategic level, the outcome of a thorough environmental analysis either justifies the chosen circular path or initiates a deviation from the current strategy. On a tactical level, supplier selection, process choices and communicational decisions may be strengthened by knowing the environmental impacts of these decisions. At an operational level, knowledge about emissions and energy flows may help sustainable decision making during new product developments; e.g. What materials are suitable for recycling?

Secondly, the logistics of the new circular concept are not fully determined yet. Therefore, a quantitative model that provides Auping insights of logistic decisions, could be helpful both on sustainability and economic grounds. In this thesis a model will be developed that approaches the dynamics of the new circular supply chain, including the use-, and end-of-life phase of the product. Besides, a scenario analysis will be performed to compare various scenarios for the conventional mattress.

In addition, to achieve Auping's vision to have a fully circular product base by 2030, there is an overall need for a practical, reliable and efficient tool to measure the environmental impact of all future products. As this is the first time a complete product life cycle analysis is utilized for Aupings products, the knowledge about these frameworks on forehand is limited. This research can provide the company insights in what tools are available, what is practically feasible and what are potential implications for this kind of analyses. Overall, in this thesis there will be a special emphasis on decisions making and assumption setting in a consequent and transparent way.

Summarizing, Royal Auping is facing the following three problems:

1. Auping is lacking a quantification of the environmental impact of the new circular mattress Evolve.
2. The logistical contribution to the environmental impact is unknown.
3. Currently, Auping does not own a quantitative tool to approach the environmental impact of new developed products.

1.4 Research aim and main questions

The introduction of the new Evolve mattress line, brought up various environmental related questions. The main objective of this research is to provide Royal Auping insights in the environmental impact of the Evolve mattress by evaluating its complete life cycle.

The main research aim is hereby formulated as:

"Quantify the environmental impact of the circular mattress Evolve, by the use of a relevant and reliable tool"

This main research aim will be answered through three main research questions:

- **"Which of the existing environmental impact methodologies is the best fit to quantify the impact of the new circular mattress?**
- **"What process information is needed to quantify the life cycle impact of the mattresses"?**
- **"If any, what environmental benefits can be expected by the new circular mattress?**

To evaluate potential benefits of a circular business model effectively, the VIVO mattress is taken as benchmark product. For both product lines, the effect of the mattress on the environment is not determined yet. Therefore, the complete life cycles of both products will be evaluated. Since this is Auping its primer Life cycle analysis, a significant amount of data needs to be gathered.

For practical reasons, the research shall be scoped to a part of the environmental spectrum. This is done by first evaluating the mid and endpoint indicators for life cycle analysis and selecting the most relevant one. For the life cycle analyses, special attention is put on the differences between both exemplars, with respect to recycling and end-of-life phase.

1.5 Project structure and research sub-questions

Figure 1 outlines the research framework. The numeration coincides with the different chapters of the research. The study is mainly based on the model of the ISO 14040 series for LCA studies, a well-established standard for Life cycle assessments.

As can be seen in the figure, in Chapter 1 the problem analysis and the research questions are defined and the structure of this document is given. Subsequently, Chapter 2 elaborates on the background, relevant literature, the end-of-life phase and the environmental impact focus.
The dashed area around Chapter III to V coincides with the proposed LCA framework, as given by the (ISO-14044:2006). In Section 2.2.2 further explanation of this framework is given.
Chapter 3 describes, the goal and scope based on the LCA method. This chapter sets the boundaries of the entire LCA. In Chapter 4, the life-cycle inventory analysis and impact analysis is given, that involves the data collection and data evaluation respectively. In the last section of this chapter, the uncertainty will be evaluated. Chapter 5 describes the transportation flows in the system. This information is used as input for the life-cycle inventory analysis, but also used directly for some more general efficiency discussions. In Chapter 6 "interpretation", the results of the LCA are provided and evaluated. Then, the conclusion and discussion of the results are discussed in Chapter 7, as well the grounds for further research. Eventually, in the Appendix amongst others an illustration of the systems can be found and specific modelling decisions for both life cycles are explained.

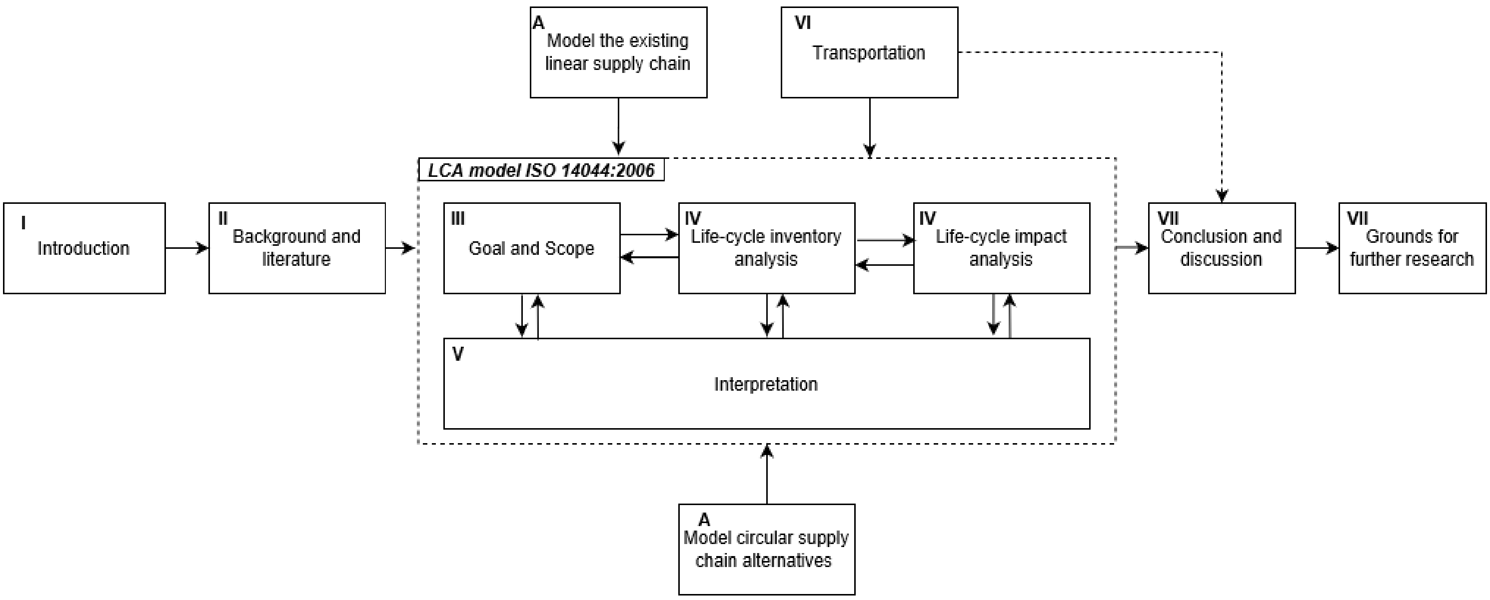


Figure 1. The research framework. The numbers I-VII refer to the chapter numbers in this document. Letter A refers to the appendix

For project structure discussed above, certain sub-questions are defined. By answering each of these questions, the overarching problems defined in Section 1.3 will be solved. At the first page of each chapter, these sub-questions are given as well.

I. Introduction

In the introduction, the goal and relevance of this study is explained. The following sub-questions were answered:

- Why is this research needed for Auping?
- What is the research goal?
- What research questions will be answered?
- How does the framework of this research look like?

II. Background and literature

The purpose of the chapter "background and literature" is two-folded:

- Provide Auping insights on how environmental impact can be measured.
- Provide relevant background information for this specific mattress life cycle analysis.

Therefore, a foundation based on literature is important. The literature study should provide insights in the market acceptable standards concerning sustainability measurement. Furthermore, the products' end-of-life processes require special attention, as these are strongly related to the circular concept. Therefore, the different forms of recycling and waste processing concepts shall be investigated. As a consequence, the following sub-questions are answered:

- What is the relevance of circularity?
- What is the new circular concept of Auping?
- What products are studied in this research?
- What methodologies and tools can be used for environmental impact researches and which is most relevant?
- What relevant mattress impact data is available in literature?
- What is the environmental scope of the study?
- What are relevant end-of-life processes for this thesis?

III. Goal and scope

In the first step of a LCA, the goal and scope of the study are defined. Hereby, the functional unit, system boundaries, and other structural decisions are set. For both systems, the linear supply chain and circular supply, a description of the flows is given. The following sub-questions are answered here:

- What systems are studied?
- What functional unit is used to express the results of the study?
- What system boundaries are set for both systems under study?
- What allocation procedures are used?
- How is the data collected?
- What quality requirements are set?
- How is the data quality guaranteed?

IV. Life cycle inventory and impact analysis

In Chapter 4, the environmental inputs and outputs are collected for all modelled processes and materials. This contains the site specific data (primary data), the data of generic required for all unit processes sources (secondary data), energy sources, material flows and wastes. The following sub-questions are being answered here:

- What inventory data is used to model the different phases in the life-cycle?
- How can the material waste flows be approached?
- What energy resources mixes are assumed for the processes?
- What different end-of-life scenarios are relevant to evaluate?
- What uncertainties can be expected regarding to the collected data?

V. Transportation

The transportation chapter describes the movements of materials in the lifecycles of the mattresses. Furthermore, various relevant transportation scenario's for the end-of-life phase are discussed. The following sub-questions are being answered here:

- What aspects of transportation affect the carbon footprint?
- How does the transport network of both life-cycles look like?
- How can the average transport distances be estimated?
- What impact can be expected for each transport flow?
- What are relevant transport scenarios to evaluate?

VI. Interpretation of results

In the interpretation phase, the carbon footprint results of the study are presented and evaluated. This chapter is divided into three parts. The following questions are answered here:

Therefore, the following research questions will be answered in Part 1 and 2:

- What is the recycling potential of the Evolve, based on the first tests?
- What cost savings can be expected by recycling of the Evolve
- What is the carbon footprint of the conventional mattress Vivo?

In part 3 the following questions will be answered:

- What would the carbon footprint be for both mattresses for full waste incineration?
- What carbon footprint can be expected for the Evolve, assuming various scenarios?
- What parts in the life cycle of the mattresses contribute most to the carbon footprint?
- What are the practical advantages and disadvantages of each alternative?

VII. Define grounds for further research

In this part of the study, answers to the research questions (conclusions), recommendations and future research suggestions are given. Lastly, the limitations of this study are given.

2. Background and literature

In this chapter, relevant background information for the remainder of this thesis is discussed. Furthermore, the decision on what environmental indicators to focus, is being made.

The following questions will be answered here:

- What is the relevance of circularity?
- What is the new circular concept of Auping?
- What products are studied in this research?
- What methodologies and tools can for environmental impact researches and which is most relevant?
- What relevant mattress impact data is available in literature?
- What is the environmental scope of the study?
- What are relevant end-of-life processes for this thesis?

2.1 Auping's new circular concept

First, the concept of circularity and Auping's circular solution are explained. Then, the two mattresses for which the impact is evaluated are elaborated on. Then, different tools for environmental impact research are evaluated. Subsequently, the relevant end-of-life aspects are discussed for this LCA.

2.1.1. The relevance of circularity in the mattress sector

People are exhausting planet earth resources at extreme rates. According to the United Nations, the consumption of materials such as fossil fuels, metals and minerals are expected to be doubled in forty years from now (UN 2020). In addition, the predicted global waste production is expected to rise by 70 percent, as early as in 2050. Both on European level and national level, goals are set to achieve a more circular economy. The Dutch Government released three goals (IenW 2016), that have to make a fully circular economy in the future possible. These are:

1. A strong decrease of the use of feedstock, by improving the efficiency of material use in production processes.
2. If new feedstock is required, as much as possible sustainable produced, renewable (non-depleting) and broadly available feedstock is used.
3. Developing both new production methods and new circular concepts.

By these goals, the Dutch government ought to achieve the ultimate aim, a completely circular economy in the Netherlands by 2050. However, these goals are far from met in the mattress industry in this country. On a yearly base, 1,2 million mattresses are discarded in the Netherlands only. (IenW , 2019) Two third ends up directly at waste processing, while one third is re-cycled as base material or filling material of different products e.g. Judo tatami filling, under carpet, or re-used in case of the steel springs (IenW , 2019). From an energy perspective, this concept can be defined as a 'delayed pulse', what refers to the delay (by the lifespan of the secondary product) of the release of GHG to the atmosphere by waste incineration or landfilling. Because, after this secondary lifespan the material will most likely become useless, as upcycling is not feasible for mixes of polymers. Until now, no cost-effective business case could have been developed for the over a million discarded mattresses(IenW , 2019).

EPR, Extended Producer Responsibility, is a policy approach whereby producers and importers are given significant responsibility for the post-consumer product life. (OECD 2004). To motivate organizations to take this responsibility, governments can use incentives. Companies that contribute positively to this striven are rewarded (e.g. by a reduced tax) and vice versa. The "EU framework directives on waste flows" proposed a list of minimum requirements for national ERP policies. To contribute to a more sustainable industry, representatives of the mattress industry are setting up EPR guidelines for this specific sector, that they will present and want to set as the new standard (IenW 2019). What and how the performance of the companies, in this specific sector, is going to be measured is not known yet. However, Life cycle analyses may be one of the involved tools, which makes it even a more relevant tool to evaluate in this thesis.

Figure 2. Illustration of an exhausted earth, by illustration.com

The post-consumer product life is often denoted as the end-of-life of a product. In this thesis, by the end-of-life, all post disposal processes are meant, from waste transportation, until either waste processing or recycling. Besides landfilling or incineration, with a complete loss of withheld energy, there are various opportunities to maintain (a part of) the invested energy. These include:

1. *Re-use*: The direct use of products or parts of products, whereby little or no reprocessing is required. Refurbishing of cell phones, can be a typical example of re-use.
2. *Mechanical recycling*: Material is transformed into 'new' raw materials by force and heat. Hereby, the polymers essentially remain intact.
3. *Chemical recycling*: There are various forms of chemical recycling. For this particular thesis, the most relevant form is 'total depolymerization'. Hereby, first polymers are brought back to monomers. Thereafter, the obtained monomers can be used as source for new polymer materials.
4. *Waste incineration with electricity or heat recovery*: The incineration of materials cause a certain by-product, heat energy. This energy can be used directly for other processes that require heat, or can be transformed into electrical energy. However, this type of energy preservation yield a very low efficiency, most energy is lost.

The option that yields the highest overall energy efficiency, depends on the material characteristics and the efficiency of the end-of-life processes. In this thesis, special focus will be put on the re-cycling and re-use of materials. In Section 2.3 more emphasis is put on these different end-of-life concepts.

2.1.2. Aupings' path to sustainability

The current innovation development is not the first step Auping took towards a more sustainable society. The invention of mesh based beds with extreme lifespans in 1890, can be seen interpreted as the early durable evolvements of Royal Auping. Still, all mesh based bases of Auping have a guarantee period of 35 years, and are often considered to be an investment for a lifetime (Auping 2020). Thereafter, various sustainability initiatives have been initiated by the company, such as:

1. The Auping Auronde bed, released in 1973, is designed to last a life time. By its modular design, parts can be either upgraded or repaired easily. Besides, Auping actively promotes to get old beds of this type be upgraded, to meet the current aesthetic and comfort standards, without unnecessary feedstock use.
2. In 2011, Auping was the first worldwide mattress producer achieving the Silver Cradle to Cradle certificate, for their developments of mattresses on circular grounds.
3. In 2014, Auping moved all production facilities to an industrial area in Deventer. Hereby, the complete production process has been transformed according to various lean principles. By the centralization of all production activities to one location, transportation can be minimized, and problem causes could be recognized in earlier stages. For example, if a certain tact time is not met, earlier processes can be inspected on possible irregularities. Furthermore, stock of components and finished product at the Auping facility is limited by the Kanban system: production at each production station only takes place after a ticked arrived.
4. In 2020, Auping received the Bcorp certificate, an acknowledgement for meeting the highest standards of verified social and environmental performances after intensive evaluation.

By the new circular mattress, Auping will be able to consolidate their sustainable position and image, as well motivate the mattress market, governments and individuals to contribute to a more sustainable world.

Figure 3. Aupings' Euroika-set, complete with the typical Auping Mesh base

2.1.3. Auping's new circular business concept

In collaboration with DSM Niaga, Royal Auping released in 2020 the circular mattress Evolve. According to Auping, this is the first circular mattress worldwide: material of former mattresses is used to build new mattresses, without loss of quality. It is to be expected, in line with the vision of the company, that the circular product base will be expanded in the near future.

For Auping, the Evolve has been the first product development process, in which circularity has been a strict requirement for all components and base materials. Commonly, products are a result of a long evolution trajectory; every version is an improvement of its earlier model. The Evolve has been developed from scratch, by evaluating all functional layers that shall be in a bed. These design changes resulted in an altered production process too.

Two principles underneath this circular potential are:

1. Material composition
2. Modularity

Material composition

The first principle yields the replacement of product layers composed of various materials, such as poly-urethane, viscose and polypropylene, by a single material known for better closed loop recycling characteristics, polyethylene terephthalate, PET. As a consequence, the new mattress is mainly composed of two materials: steel springs and PET[2]. PET is a group of polyesters that is known for its great recycling ability, with its well-known applications in the plastic bottle industry. For steel, there is already a well-organized recycling system in The Netherlands.

It is not clear yet whether the recycling process will take place in the Auping factory, or in a partner facility. Therefore, various scenarios will be evaluated in this thesis for the end-of-life of the Evolve mattress.

Modularity

Secondly, the principle of modularity plays an important role in this new mattress concept. The specific thermoplastic adhesive in the Evolve mattress, is selected to ease disassembling. By heating the mattress shortly at around 130 degrees (Auping 2020), the glue is weakened and the parts can be separated easily. Traditionally, the steel in mattresses needs to be extracted by a shredding step, with extreme wear to the machinery as a consequence. By this new disassembly method, steel springs can separated from the PET effectively, what facilitates efficient recycling.

Figure 4. Cross section of the Evolve mattress. All layers can be disassembled conveniently

To date, the supplier base and assembly processes of the Evolve are to a great extent developed. Furthermore, the regular product development process is finished; the production systems delivers products of the desired quality level (Auping 2020). However, the end-of-life of the Evolve mattress is still under development. Closed loop recycling of textile is still in a pioneering phase, thus significant testing is required to obtain the right output quality and efficiency. In the mattress industry, the assumed standard life span of a mattress is ten years (Auping 2020). As a consequence, there are various years left to organize an efficient end-of-life system. Hereby, quantitative underpinning is required to justify the related decisions. In Figure 5, the current standings of the development process of the circular mattress Evolve is given.

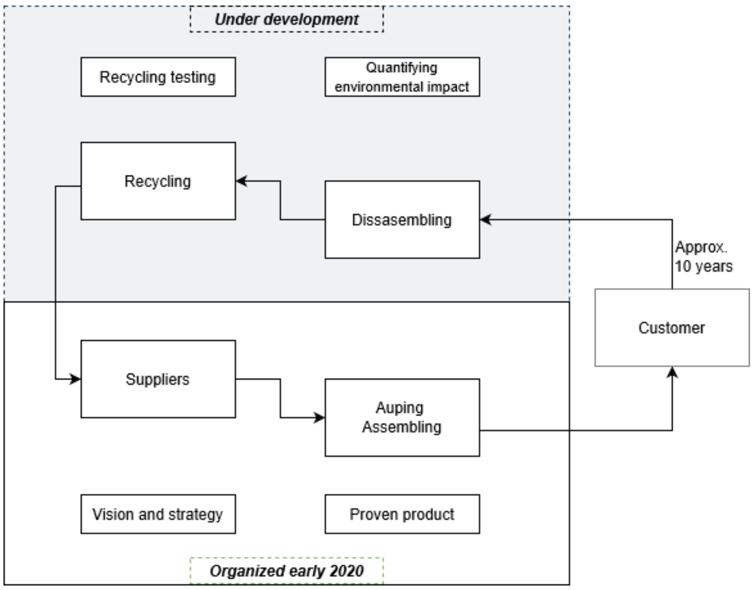


Figure 5. The current standings for Evolve. The light grey area is still under development, the white area is yet organized

[2] The non-woven layers contain a small amount of melting fiber, that is required as binder. This fibers consist of a mantel (non-PET polyester) and a core (PET polyester). The effect of this fiber on the recyclability of these layers, is currently being researched.

2.1.4 The two mattresses in this comparative LCA

This thesis is a comparative analysis of two different mattresses manufactured by Auping. In order to find the quantitative impact for both mattresses, first the lifecycles of both mattresses are modelled. In the remainder of this thesis, by the "conventional" and "circular" system, the lifecycles of both mattresses are meant. The two researched systems are schematically drawn in Figure 6.

In the upper half of this figure the conventional system, the life cycle of the Vivo mattress, is shown. From the disposed mattresses, a part is recycled and another part flows into waste processing (incineration). There is no circular flow and all materials at the supply are assumed to be virgin.

In the lower half, the life cycle of the Evolve mattress is given. This mattress is made out of materials known for their good recycling properties. For the disassembly and recycling processes, it is not fully defined by whom and how this will be utilized. That is why a dashed box is drawn around these processes. After recycling the PET material are returned to the component suppliers, where the material will be used for new component production. This can be seen as a circular or closed loop system. Closed loop refers hereby to the material flow in the process: waste material from a product, will be recycled and replace (a part of) the virgin material for the same type of product (as if it is a closed loop). Both mattresses fulfil the identical function for its consumer: Being a comfortable and supportive layer for the user while sleeping, for approximately a period of 10 years.

The complete lifecycle of both mattresses can be divided in 5 phases: Supply, Manufacturer, Distribution, Customer and End-of-life. A more detailed visual life cycle overview for both systems can be found in Appendix 1. In the following paragraphs, both life cycles will be explained.

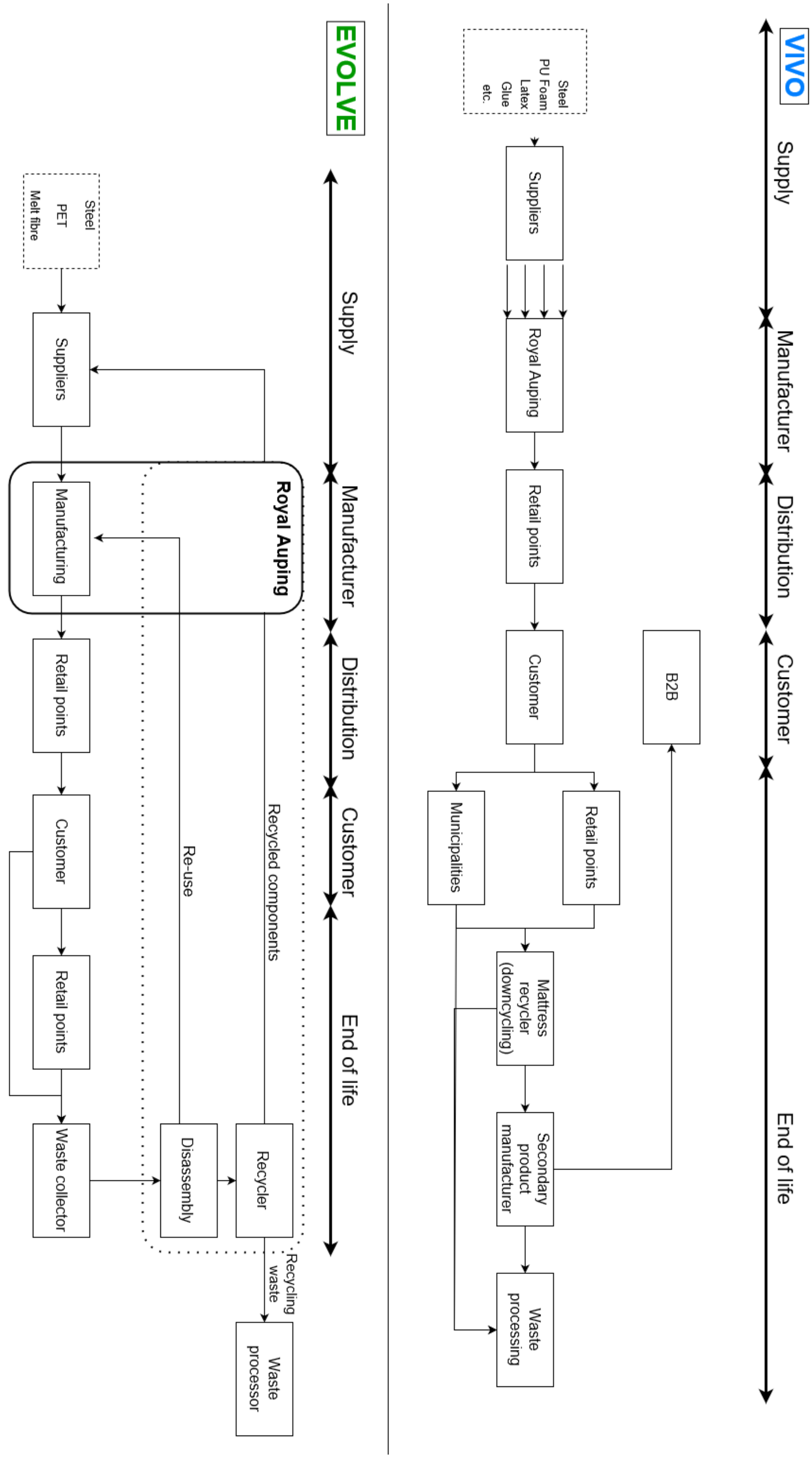


Figure 6. Simplified version of the life cycles of the Evolve and Vivo matttress, with its phases

Vivo system

The suppliers of the Vivo mattress only have one specific task in this system: supplying the components to the manufacturer. After all components are collected by Auping, they are assembled. Hereby, the components will be interconnected by various processes, mainly consisting of sewing and gluing steps. This process is organized by a so called flow-shop production system, whereby products are produced piece by piece. The semi-finished goods are transported between the different processes by either conveyor belts, or human interference. After packaging, all mattresses that passed the quality check, are shipped to the retail points. From here the mattresses are distributed to customers. Auping works according the make-to-order principle, that is: the assembling/producing of products starts, only after an order is placed. As a result, there is no stock of these mattresses in the factory or in the distribution chain.

On average, mattresses will be used for 10 years (Auping 2020), after which they are either collected by retail (after buying a new mattress), or brought to the municipality waste collection. From here, the mattresses are either collected by a mattress recycler, or brought to a waste processor. Currently, there are two companies that recycle used mattresses In the Netherlands. These are "Retour mattress" and "Matras Recycling Europe".

These companies disassembly the mattresses as far as economically feasible, and further process the separated flows. For each of the components different activities are in place. The steel springs in the mattresses are first separated by a shredding processes, whereafter they are send to an external steel recycling company. The foam layers are mechanically recycled, resulting in a foam consisting of a polymer mix called bonded foam. Potential applications of this product are insulation for floor panels and fillings of furniture. The separated textile flow is not utilized internally, but compacted and sent to companies that reprocess these fibres into secondary textile fibres. As there is no controlled inflow of the materials in this recycling system, the output is a mix of fluctuating material compositions. In general, the separation of these mixes of different materials is either cost inefficient or technically infeasible processes. Therefore, this form of recycling is often referred to as "downcycling", as the quality of the parent plastic (during its first product life), will not be reached again in its "second life", after recycling (Enthaler 2017). For the well-known case of PET polyester drinking bottles in The Netherlands, the material of the bottles can have multiple life-cycles. This does not apply for the recycled output from the mattress downcyclers, that will most likely be recycled only once. Thus, mostly after this second life of the material, the waste will be treated by either landfilling or waste incineration (Enthaler 2017).

Evolve system

In contrast to the Vivo mattress, the Evolve mattress life cycle includes a circulating flow for all non-steel materials. The suppliers will use the recycled granulate from used mattresses, for the production of new components. Thus, the recurring flow of recycled materials partially replaces the virgin inflow of polyester. For now, Auping assumes to send materials in recycled form (as granulate) to the suppliers. However, if it appears to be more beneficial on economic or environmental grounds to send disassembled components as whole to some of suppliers, this may become the standard. In that case the suppliers will be held responsible for the recycling of the materials, in an energy efficient manner. In this LCA, all the material recycling is assumed to be organized by Auping. In Figure 7 a schematic representation of this "circular" supply process for the Evolve is given.

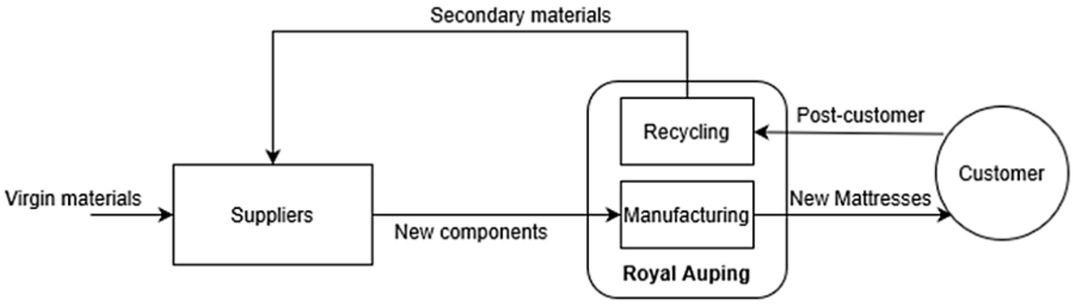


Figure 7. Simplified representation of the circular system. The flow "secondary materials" represents either the recurring flow of all non-steel components or recycled plastics (as granulate or pallets)

After all components are delivered at Auping, the mattress will be manufactured. To a great extent, the same assembly processes (sewing and gluing) are required for the semi-finished components for both the Evolve as for the Vivo. For the Evolve though, the final assembly of semi-finished product (gluing) will be utilized by a robotic system. This system is engineered to increase the production efficiency, as the product does not need to be moved between the production processes. While this robotic system is still under developed, the required actions will be done manually by man power. In contrast to the Vivo, mattress production waste material, such as cutting waste and rejected production materials, can be re-used with the aid of recycling for new mattress production. For the Vivo, most of this waste is collected and send to a waste processor, a limited amount can be used for other purposes (e.g. as felt handles for the mattress).

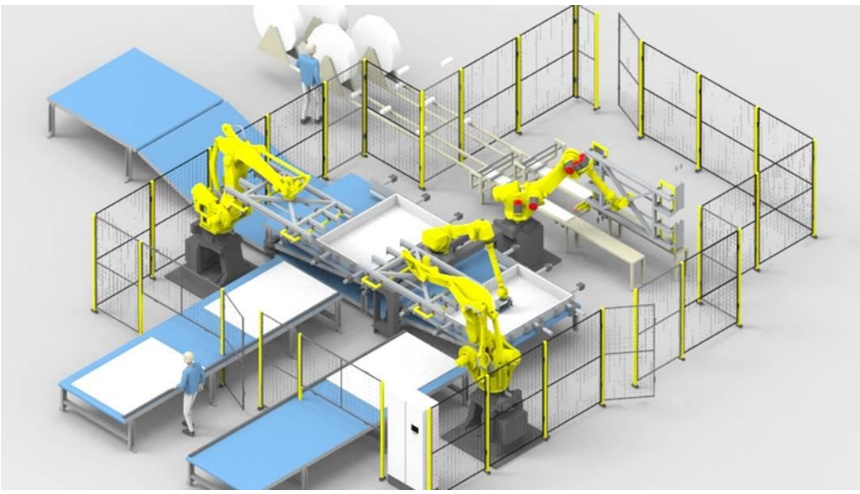


Figure 8. Concept version of the robotic assembly system for the Evolve

The distribution process of both mattress are identical. After an order is being placed, the mattress is manufactured at Auping and send to the involved retailer, that organizes the delivery to its customers. However, after the life span of the mattress at the consumer, all Evolve mattresses will be collected by Auping, free of charge. The mattress passport, an electronic chip integrated in each mattress, keeps track of important information of that specific product. By this Auping will be able to track the mattresses and will know the exact composition of that specific exemplar.

The collected used mattresses will be disassembled at Auping. This disassembly process will be done by adding heat energy, whereafter the thermoplastic adhesive will become liquid again. This process is currently being tested at Auping. The disassembled PET components will be sorted per layer, to be recycled separately. There are minor differences in material composition for these parts, due to melting fibre and the use of paint. By recycling the sorted/grouped flows, this problem can be avoided. Depending on the recycling efficiency, a small part of the material will not be recycled. This waste flow will most likely follow a regular waste path for plastics, waste incineration with electricity recovery. The used steel springs can follow two paths: recycling or re-use. For all steel springs that will be recycled, these are brought to regular steel collecting points in the Netherlands, identical with the Vivo springs. For re-use, the springs are first checked on quality, and then cleaned and re-used. The recycled material is send to the suppliers. In a sense, the recycling factory fungates as "supplier" for the component suppliers.

For now, the steel recycling process is still under development. Therefore, various scenarios will be considered in this thesis, for which the results are given in Chapter 6. Furthermore, the location for the recycling process and the exact recycling process for each layer is not known yet. Therefore, an impact estimation for various geographical alternatives is provided in this thesis. The ratio between new material and old material in the new products, will depend on the size of old mattress flow, the recycling efficiency and the production amounts for the new mattresses (sales). Therefore, various scenarios for these parameters will be evaluated in Section 6.2.2.

2.1.5 Conclusions on circularity

At the light of this section, the following conclusions are drawn:

- Circularity, the aim to eliminate waste and have cyclic resource flows, is an important spearhead for (inter)-national policy makers. The Dutch government has the goal to be 100% circular in 2050
- The new mattress Evolve, is Aupings' answer to this circular striven. Its recycling potential is defined by two aspects: a specific material composition and modular design.
- This is a comparative LCA: The circular mattress Evolve is compared to a linear exemplar, the Vivo.
- The Vivo has an open loop recycling system; the recycled content serves another product system. From a material perspective this is called downcycled, as the material value is affected.
- The Evolve has a closed loop recycling system; The recycled content can be used for the same function in the mattress, without loss of quality.

2.2 Environmental impact research

There are various methods to measure the environmental impact of products or services, of which a selection is given in this section. First, the methodologies CTI, Circulytics and Life Cycle Analysis, are discussed. For LCA, first the methodology is explained, then various related tools are evaluated. Subsequently, the framework ReCiPe is explained, from which one impact indicator is selected in the subsequent section. Then, the standards for LCA studies are discussed. Finally, conclusions are drawn for the earlier sections.

2.2.1 Metrics for circularity and environmental impact.

The environmental impact of products, services and companies incur energy and material flows. The concept of circularity is often used to refer to the effective conservation of this energy and materials. Based on mostly qualitative evaluations, governments and companies were already able to form visions and strategic goals regarding circularity. However, accepted standardized quantitative tools are required, to stimulate effective company (management) and governmental (regulative) decision making and provide tactical and operational guidance. Recently, various tools are released to define a company or product's circularity, that all have different scopes. Several promising quantitative tools are:

1. Circular Transition Indicators, CTI, initiated by WBCSD early 2020.
2. Circulytics, initiated by the Ellen Macarthur foundation early 2020.
3. Life cycle analysis[3], LCA, well established environmental tool. Roughly since 1975.

Circular Transition indicators

The first method, "CTI", is an indicator for the share of inflow material and energy that is considered circular (recycled or re-used), against the total required inflow/energy in the life cycle. This is a rather straight forward methodology and is simple to implement, as it requires only the bill of materials and an efficiency of the recycling process. Nevertheless, as the environmental impact is only evaluated from a material and energy flow perspective, the outcome may not be viable for all situations. One example: For a certain product, a CTI of 90% may indicate a great circular performance. However, if the recycling process itself is very harmful, the overall system impact may still be unsatisfactory for the environment.

Circulytics

The second method "Circulytics", is a more labour intensive evaluation of the systems circularity. This method, initiated by the Ellen Macarthur foundation, claims to measure the entire company's circularity, not just the energy and material flows (Ellen Macarthur Foundation 2020). Circulytics deviates possible gain into two categories: "enablers" for change and "outcomes". The enablers focus on aspects that are potentially important for company-wide transformation to occur. The outcomes build on existing measurement frameworks of material flows and can be seen as reflection on the circularity of the company today (Ellen Macarthur Foundation, 2020). By various indicators on seven distinct themes, an overall score for the company can be defined, given in a similar manner as the EU energy labelling (A+ for lowest, E for worst.)

Figure 9. Schematic representation of the circulytics methodology (Ellen Macarthur Foundation 2020)

[3] LCA is already a popular tool to measure environmental impact. Modelling circularity can be challenging in LCAs.

Life Cycle Analysis
Lastly, the methodology Life Cycle Analysis, LCA, is both a quantitative and qualitative instrument to measure the impact of products or processes. By evaluating the complete life cycle process (limited by the study scope), an indication of the product or process burden from an environmental perspective can be provided. This analysis can be done for a great variety of impact categories (e.g. global warming, toxicity). LCAs are not necessarily intended to indicate the circularity, but the collected data can be used to serve the other metrics, such as CTI.
For the following reasons, LCA is selected as framework for this study:

1. LCA is a well-known and established methodology which eases potential communications between involved stakeholders, both internally and externally.
2. This methodology evaluates the complete life cycle, which can result in valuable information for future decision making. Such as, purchasing decisions, logistical improvements and material choices with respect to recycling.
3. The gathered information can reduce costs, by decisions that could yield more efficient resource use. (P. van der Lucht, J.G. Vogtlander 2015)
4. The upcoming introduction of extended product responsibility, will involve a measurement tool for the environmental performance of products and services. LCA is one of the tool that is currently being discussed to serve this purpose in the bedding industry. Auping wants to extent their knowledge about this framework.

The CTI and Circulytics are recently released metrics (early 2020) and therefore considered less well-established methodologies. As a consequence, information about the performance, limitations and compatibility of these tools, is scarce. Considering the fact that this is the first circular impact study of Auping, the most established methodology, LCA, is chosen for this study. In future studies, evaluation of the mattresses by other metrics, can be contributing. In the next section, a thoroughly explanation of this method is provided.

2.2.2 Life cycle analysis

In LCAs, the environmental aspects of product's life cycles are assessed in a systematic manner. Depending on the defined LCA scope, the complete life cycle, from raw material extraction to the end-of-life, or a specific part of the life cycle can be evaluated. LCA can focus on one or more environmental impacts, such as the released greenhouse gases, resource depletion and human toxicity. These impact indicators are further elaborated on in Section 2.2.3.

The Dutch ministry of Health and Sustainability defined LCA as follows:

"In LCA, the environmental impact of a product or activity is being assessed throughout its total life cycle. From the extraction of resource materials onto the waste and waste treatment or recycling states. Various Environmental impacts are being analysed." (Ministerie VROM 2008).

According to the same department[4], this can be a relevant tool for various institutions for decision making, such as (RIVM 2018):

1. For governments, to shape environmental policy.
2. For science, to support environmental policy
3. For businesses, to implement environmental policy

In other words, LCA assessments can inform companies and organization on how products and processes affect the environment, and can help to adjust their decision making accordingly. In order to perform a LCA in an organized and effective manner, various frameworks can be used. Both the

[4]In 2010 the VROM no longer exist. All activities are redistributed to other departments such as the RIVM.

'Greenhouse Gas Protocol' and the 'International organization for standardization (ISO)' are well-recognized standards for these analyses. For arbitrary reasons, the ISO standards on LCAs are used in this thesis. Throughout the thesis, specific citations and refences to these ISOs are displayed in blue boxes.

The (ISO-14044:2006 sd) for Life cycle assessments, describes a four phase roadmap for LCA studies:

1. Goal and scope definition
2. Life-cycle inventory (LCI) analysis
3. Life-cycle impact assessment (LCIA)
4. Interpretation of results

This framework is schematically provided in Figure 10.

Phase 1: Goal and scope definition

In the goal and scope definition phase the product under study is described, relevant aspects of the life cycles are discussed, and the goal of the LCA is defined. The main structure choices for the LCA framework are made here. For example, setting the system boundaries. What to include in the study and what to cut off. If eventually, the goal set in this phase is fulfilled, the LCA can be considered successful.

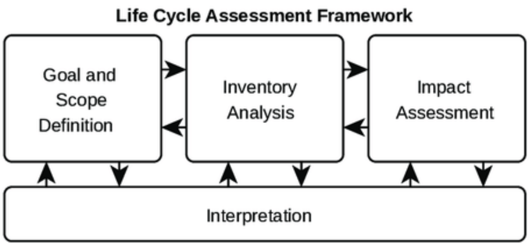


Figure 10. The framework for life cycle assessments, as proposed by (ISO-14044:2006)

Phase 2: Life cycle inventory (LCI) analysis

In the LCI phase, the environmental inputs and outputs are collected for all modelled processes and materials. For the remainder of this thesis, this data is referred to as inventory data. This information can be either site-specific, when measured at the specific location, or generic, when collected from one or more generic databases. Obtaining complete and reliable sites-specific data can be challenging and time consuming. In order to ease future consultation and to facilitate critical reviewing of the data, the collectable data should be recorded in a structured and transparent manner. The quality of the LCA results depends heavily on this phase.

Phase 3: Life cycle impact assessment (LCIA)

During the LCIA phase, the collected data in the LCI is translated to the desired environmental impact categories, mid or end-point indicators. These are various categories of environmental impacts, such as global warming or human toxicity. In Section 2.2.6 the principle of mid and end point indicators is further explained. This LCIA phase consists of the following sub steps (Nieuwlaar 2013):

1. **Classification**: Hereby the flows are coupled to the chosen impact indicators. A list of all relevant flows is made for every researched impact indicator. *An example: What specific flows in the inventory data affect human health? (indicator: human toxicity)*

2. **Characterization**. In this step the collected data is converted to the desired impact indicator. "All flows are multiplied by a factor which reflects their contribution to the environmental impacts" (Golsteijn 2014). *An example: For Global warming potential, the impact*

of a product is often given in kg CO2 equivalents; the impact that a certain amount of CO2 would have on global warming. For the use of electricity a certain factor is used to convert the energy amounts to kg CO2e.

3. **Normalization** (optional): The obtained values are compared to a certain reference value. The outcomes of the study can be related to a certain reference numbers.
   An example: "the impact of the population of a country, or of one European citizen in a year. (Golsteijn 2014)

4. **Weighting:** The different impact categories are aggregated into one value, by applying weighting factors. This is often considered to be a debatable step, as the weights depend on what thought is important. Several organizations offer a list of weightings, that are accepted by a group of environmental scientists.

The complexity of the LCIA phase increases with the number of indicators. For example, when a LCA focusses on global warming only, this phase can be reasonably simple. The global warming

> *"In the LCIA phase of a carbon footprint study, the potential climate change impact of each GHG emitted and removed by the product system shall be multiplying the weight of GHG released or removed by the 100-year GWP given by the IPCC in units of kg CO2e per kg emission".*
>
> (ISO 14067:2018 sd)

standard (ISO 14067:2018 sd), describes this LCIA phase as follows:

Phase 4: Interpretation

In the interpretation phase, the opportunities to minimize the environmental burdens are evaluated. For an effective report, the obtained results shall be reported in the most informative manner possible (Vogtlander 2015).

Points of attention for LCA

First of all, the ISO standards suggest an iterative approach for life cycle assessments, indicated by the arrows in Figure 10. If the contribution of a certain aspect of the lifecycle (e.g. transportation) appears to be negligibly small, there shall be put no further emphasis on this factor. By this, the focus and effort will be put on the factors that have the largest impact. An iterative approach may help the life cycle analysis being utilized in a both effective and efficient manner.

Secondly, time management remains an important factor in LCAs. Performing a full LCA methodology (considering all impact indicators) may become time-consuming, for various reasons. Among others:

1. LCAs are often data intensive researches, that shall be collected from internal and external parties. Therefore, the effectiveness and reliability of this type of researches depends highly on the collaborative attitude of the concerned parties.
2. In order to understand and apply the requirements and guidelines for quantification standards, preparation of the research is time consuming as well, e.g. ISO 14067 or GHG Protocol/PAS 2050.

Furthermore, the proper tools and scoping is essential for effective and efficient LCA. Ideally, these studies will only be represented by real data from factories, so called site-specific data. In practice, data will be a mix of primary and secondary data, in line with the (ISO 14067:2018 sd) guidelines.

At last, to be considered as a full LCA, researches must fulfil the guidelines of an acknowledged standard with respect to data acquisition and methodology, including a critical review of the work (Horne et al., 2009). The critical review is yet not included in this report, but this can be a relevant issue for further research. This study will therefore not yet qualify as full LCA, but will still give a good indication of the differences between the two mattresses.

2.2.3 Review of available mattress LCA information

There is a relatively limited amount of public available LCA information on bed mattresses. The report of EU ecolabel (Cordella et al., 2013), discusses various relevant environmental studies of bed mattresses, that are not all publicly available. In Table 2, a selection of the studies discussed in this review are listed, expanded with some other studies. The studies vary in scope, use different functional units and have alternative environmental focusses.

Name of study	Year	Scope, system boundaries	Functional unit	Environmental indicators considered
European ecolabel bed mattresses, LCA and criteria proposals final report , EC	1995	Various types of mattresses **SB: Cradle to grave**	1m2 of mattress	Several midpoint indicators e.g.: Global warming, eutrophication, human toxicity, abiotic resource depletion
The Greek LCA (Boura) – establishment of the ecological criteria, EU eco label.	2004	Types of matresses Latex foam Spring interior PUR foam Scandanavian mattress **SB: cradle to grave**	1m2 of mattress	12 midpoint indicators as: e.g. global warming, human toxicity, acidification.
Furniture Carbon footprinting, FIRA	2011	19 double matresses (incl. both spring and foam matresses), **SB: Cradle to gate[5]**	A double mattress	Global warming
Environmental analysis of polyester fabric for ticking	2017	Polyester ticking made by an Italian producer, **SB: Cradle to gate**	1 kg of ticking material	More or less all mid and final indicators such as: Global, ozone depletion, eutrop.

Table 2. Overview of environmental mattress studies in literature

Several conclusions that can be drawn of these articles are:

1. The LCA research of the European commission (1995), is most similar to the current study in focus, although it has a broader environmental scope (it includes various midpoint indicators). However, the accompanied inventory data is reasonably dated (25 years old). Therefore, direct usage of these data points is not favourable.
2. The research regarding the polyester ticking (2017), does provide some insights in the energy shares of the different life cycle processes for a polyester ticking case. This ratio can be used to estimate the contribution of dyeing for the carbon footprint. Furthermore, this research uses a data certainty evaluation method using a Monte Carlo analysis that may be useful for this study.

[5] Cradle to gate includes everything from raw material extraction, until it leaves the factory "gate".

3. The FIRA (2011) furniture research, provides carbon footprint data for several categories as e.g. textile, steel, transport etc. However, all data is cradle to gate[5]. Therefore, transportation only includes a limited part of the complete transport of materials, components and products.
4. These researches report a carbon footprint between 80 and 160 kg CO2 equivalents for the mattresses in this study. However, the system bounds set and products evaluated in these researches may be different.
5. There is no (publicly) available information about closed loop mattress recycling in literature.

2.2.4 Selected generic databases for Auping's study

In LCAs, all processes are represented by gathered data points: the inventory data. This can be real data based on measurements, or generic data from a database. Most of these databases require a license to get access to the content. Examples are the global leader Ecoinvent, the Agri-footprint database and GaBi databases, that all have a great number of processes. This thesis can be seen as a first discovery of the concept LCA for Auping. Therefore, for this analysis, only openly available databases are used as generic data source. LCA researchers should be careful selecting datasets to use, as the geographical representativeness could be affected. One example:

If an Indian database is used to model an European factory, then the results may be biased. Factors such as the used technology and the energy mix used may differ significantly.

In this LCA two databases are used, that both have representative data for the life cycles affected region: western Europe. Therefore, in this theses the following databases are used:

- *Idematapp2020*: Inventory database organized by the Delft University. A set of carefully collected inventory data, based on peer reviewed literature and scientific databases of universities. According to the homepage of this dataset (Ecocostvalue 2020), the Ecoinvent database had unexpected fluctuations over its recent releases. The Idematapp may be a more stable alternative. This database is updated at least once a year.
- *Ecoinvent v2.2:* An older version of the Ecoinvent database releases, that is openly available. The data may be less representative for the current industrial field.

2.2.5 LCA (software) tools

2.2.5.1 LCA tools

To utilize a LCA in a consistent and effective manner, all data should collected and processed in a structured manner. Transparency is key, especially if the results are used for comparisons between products of different studies: Are apples compared to apples and not to pears? Besides, for the critical review, the optional step for LCA studies mentioned in Section 2.2.2 (ISO 14067:2018 sd), an external researcher should be able to understand the steps taken. There are various tools available, that adapt easily to the major databases. Famous tools are:

- *SimaPro by Sustainmetrics*: A popular standardized LCA software that uses the Ecoinvent database and the related modelling capabilities by default (Simapro homepage 2020). An additional functionality called "Collect and Share", allows a user to share results easily to non-expert colleagues.
- *GaBI4*: A software that selects the best fit database for the user, based on its geographical location. GaBi offers a broad support package, that can also assist companies in designing product with more environmentally friendly components (Homepage GaBi software sd).
- *OpenLCA*: Freeware that can be used for LCA calculation. Comes with a comprehensive package of impact assessment methods. However, this software has no standard integration with databases. As a consequence, this software requires more effort from the user.

In order to find the most suitable LCA tool for Auping, a qualitative analysis is done. Hereby, the functionality and general characteristics of the LCA software were evaluated. For 14 criteria in 4 categories, scores were given. In Table 3, the results of this evaluation is given. Hereby, the categories are:

1. Flexibility: Degree the models and parameters in the software can be altered and adapted to the wishes of the user.
2. Extensiveness: Refers to the functionality of the software.
3. Cost: The total cost of ownership. That are licencing + operational costs (invested hours).
4. User-friendliness: Refers to both the ease of using the software and additional services.

For the evaluation of the criteria, the following scale is used:

- 0 = not or barely met
- 1 = to some extent met
- 2 = fully met / completely true

Each category has an identical weight of 25%, that is an the sum of criteria within that category. All criteria that belong to the same category, have an equal weight. A total score per category is calculated, that is the weighted sum of the criteria within. These scores per software alternative are shown in Figure 11. These judgements are based on literature, mainly from the extensive LCA software evaluation of (Seto et al., 2016). Additionally, information from the official enterprise channels, e.g. from the enterprise website and user manuals, were used.

Clearly, the Gabi and SimaPro software received very similar scores in all categories. Relatively high scores for both packages are given for the categories: flexibility and extensiveness. In contrast, the Open LCA outperforms the other software with respect to costs, as it is the only open source software. The other two software packages require a paid licence. Since the LCA software is likely to be used by unexperienced LCA performers at the company, user-friendliness is a very important factor. As a consequence, the SimaPro software is advised to , as this is assumed to be the most user-friendly alternative. The fact that there is a one-year service contract included and support can be given in Dutch, is assumed to be an important advantage over the other software.

Category	Criteria	Weights	Gabi	SimaPro	Open LCA
Functionality					
	Goal and Scope Definition				
Flexibility	System boundaries can be defined by the user?	6.25%	2	2	2
Flexibility	Users input any functional unit that they want?	6.25%	2	2	2
Flexibility	Various time horizons are possible? (10, 100, 1000 years)	6.25%	2	2	2
	Life Cycle Inventory Analysis				
Flexibility	Additional databases can be added?	6.25%	2	2	2
Extensiveness	Software include a database of inventory information for the life cycle processes?	5%	2	2	1
Extensiveness	The included database(s) contain relevant data for the life cycle of Auping's products?	5%	2	2	1
Extensiveness	Software can be used (easily) for other circularity indicators (integration)?	5%	2	1	1
	Life cycle impact assessment and interpretation				
Extensiveness	Different characterization factors systems (such as ReCiPe) can be adapted?	5%	2	2	2
Extensiveness	Extensive graphical representation possibilities?	5%	2	2	1
General characteristics					
Cost	Low licencing cost ?	12.5%	0	0	2
Cost	Low operational costs (learning hours + utilization time) ?	12.5%	1	1	1
User friendly	Level of additional services available?	6.25%	2	2	1
User friendly	Practical to use for non-expert users?	6.25%	1	1	0
User friendly	Practical helpdesk for Auping (language, short lines) available?	6.25%	1	2	0
User friendly	Supports easy multi-user usage (at same time)?	6.25%	0	1	0

Table 3. Evaluation of three LCA softwares, based on it's functionality and General characteristics

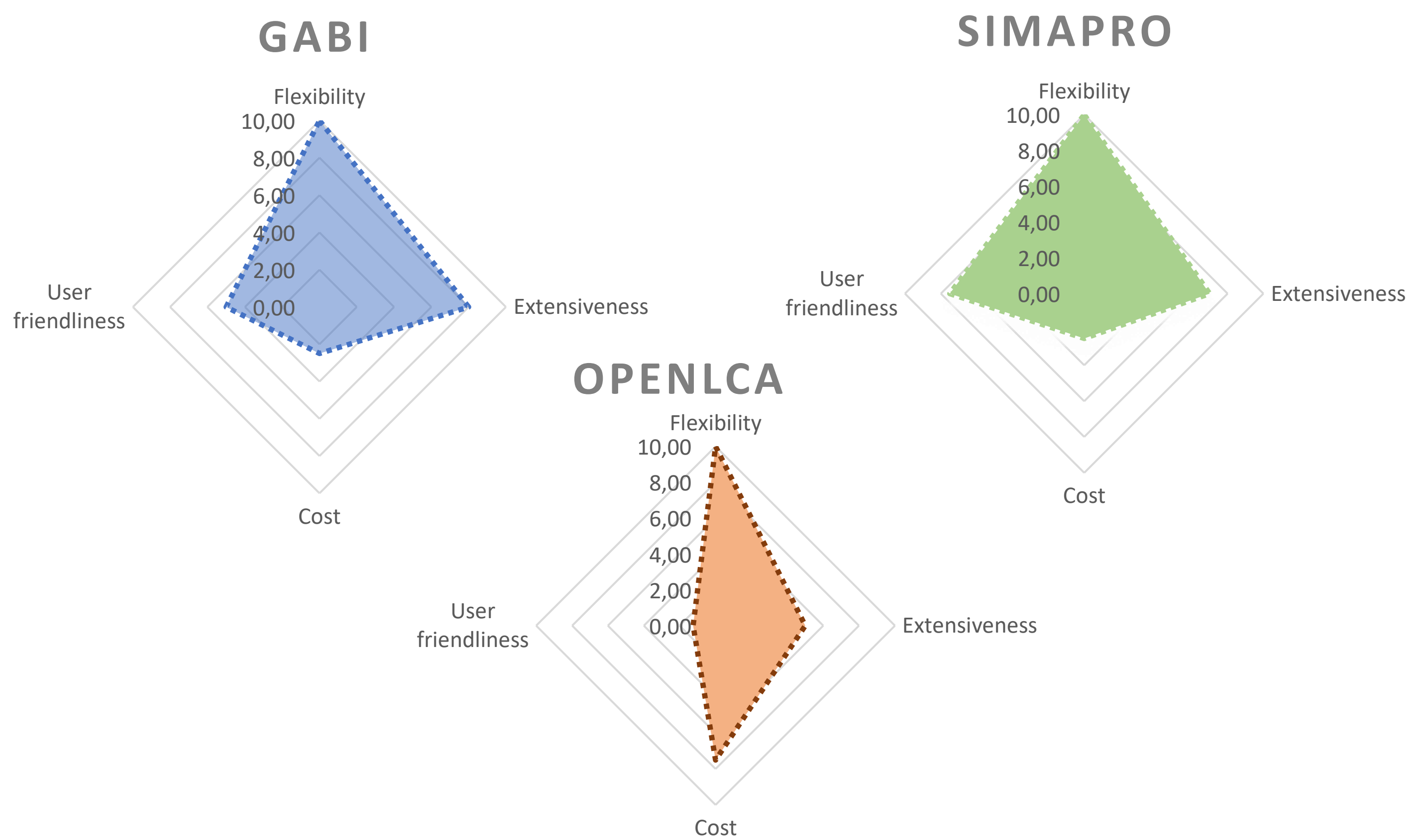


Figure 11. Spider diagrams for the three evaluated software packages. A high score means a good performance in this category. The aggregated scores per category are tranformed to a 0-10 scale

2.2.5.2 The LCA Excel tool

For this thesis, there is decided to build an excel based LCA tool. The advantages of an excel based strategy is that the involved researchers get deep understand understanding of the obtained results. All included unit processes, the chosen methods (such as allocation methods and end-of-life modelling) are specifically selected by the researcher. A disadvantage of the excel based strategy is that using of the dedicated software, more detail can be included in the calculation.

First, an overview of the lifecycles and a bill of material list of both mattresses was made. By this, the specific size of the problem could be mapped. In total, there were 67 components listed for both mattresses together. To reduce the potential workload, a lower weight limit of 1% was set for both mattresses. As a result, 31 components had to be evaluated. This size was considered manageable, thus the obtained was set as study base. The developed excel tool has the following features:

- *An impact dashboard***:** a visualization of the results was created from the early start**.** LCAs are iterative processes. Therefore, the relative contribution of a step, should define what is researched more intensively and what is abandoned. By continuously monitoring the total carbon footprint of all added elements, there could be focused on the most relevant aspects. One example: *Transportation was expected to have a minimal contribution to the mattresses carbon footprint. However, as the first transport legs were modelled, these appeared to be of a significant magnitude. Therefore, more emphasis was put on the modelling of transportation.*

- *Separate lifecycle sheets***:** All phases in the life cycle are modelled on separate sheets. Hereby, the impact of each lifecycle could easily be extracted from the tool.

- *Component dedicated sheets:* One sheet is dedicated to every component. By this, the researcher can easily modify the system, for potential supplier changes and product composition revisions.

- *Automatically updating graphs***:** figures are updating immediately for changes in the data. The most relevant figures are created in a structured manner. Therefore, for changes in data, these figures update accordingly.

- *Secondary databases listed:* All collected secondary data is listed on one sheet. If better data is found, the old data can be replaced, and the complete model will be updated automatically.

- *On and of button analysing tool:* The analysing tool for uncertainties, can be turned on and off. The Monte Carlo simulation can be used to evaluate the data uncertainty using two different distributions. To decrease the computational effort, this tool can be turned off if not needed

On the following page, various screenshots of the excel tool are provided, together with a short explanation.

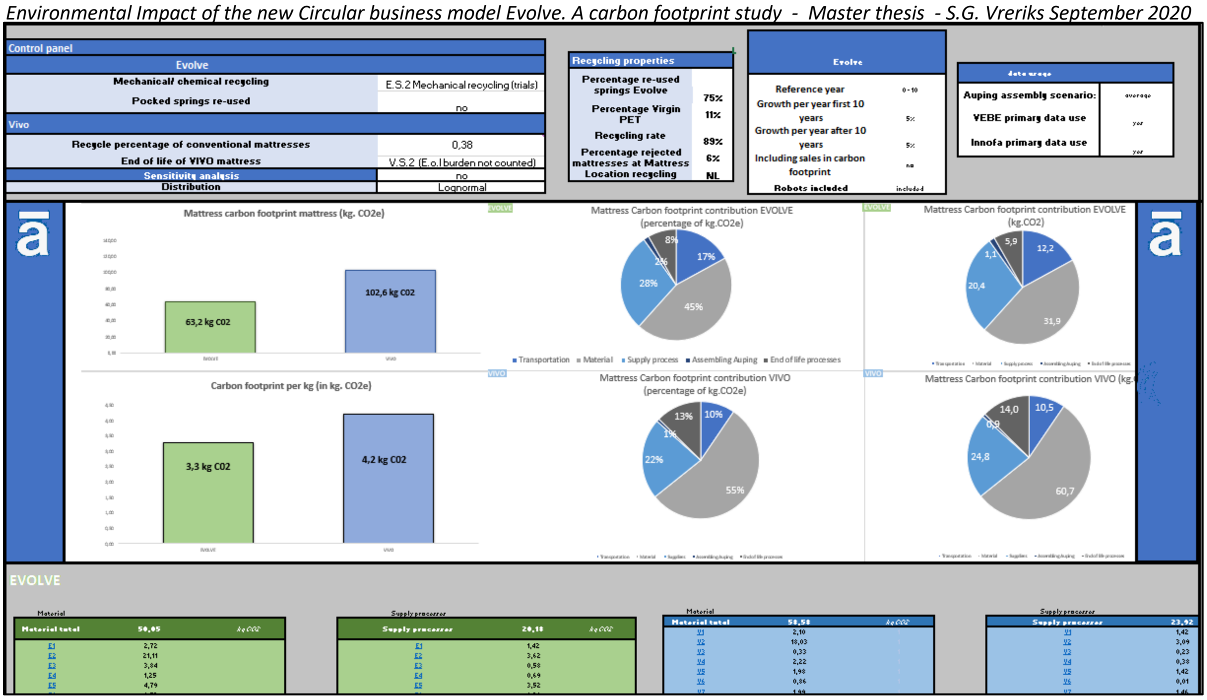
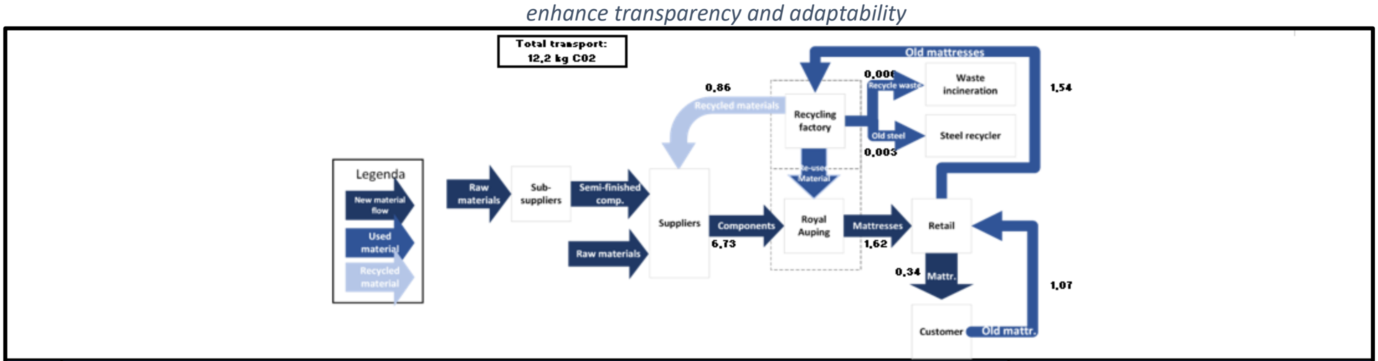


Figure 14. Screenshot of the dashboard of the excel tool. The different buttonnes can be used to see the carbon footprint of the mattressses for various scenarios. Made for the iterative approach

E1 Pocket spring PET pocket	Total CO2 for component	4,60	kg CO2 eqcuiv./ kg
	Data type	**Value**	**Unit**
	PET polymer pellet production	2,12	kg CO2 eqcuiv./ kg
	Spinning extruder polymer filaments (80-500 dtex)	0,73	kg CO2 eqcuiv./ kg
	Calendering, rigid sheets/RER S	0,38	kg CO2 eqcuiv./ kg
	Amount of PET re-used	0,00	
	Amount of PET needed	1,28	kg
	Amount of PET pallets spun	1,28	kg
	Amount of Pet filaments bonded	1,28	kg
	Amount of component transported from Agro to Auping	1,13	kg
	Amount of component transported from Italfeltro to Agro	1,21	kg
	Truck+trailer 24 tons net (max weight/volume ratio 0,32 ton/m3) (m3.km)	0,027	m3km
	Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tkm)	0,084	tkm
	Kilometres from sub-supplier - supplier	168	KM
	Kilometres from supplier - Auping	1296	KM
	Carbon footprint Parameter	**unit**	**value carbon footprint**
Material			
PET polymer pellet production	2,12	kg CO2 eqcuiv./ kg	2,72
		Subtotal material	2,72
Production			
Spinning extruder polymer filaments (80-500 dtex)	0,73	kg CO2 eqcuiv./ kg	0,93
Calendering, rigid sheets/RER S	0,38	kg CO2 eqcuiv./ kg	0,48
		Subtotal Processing	1,42
Transport before supplier			
Transport from sub-supplier - supplier	0,084	kg CO2 eqcuiv./ tonnes. Km	0,26
Transport from supplier - Auping	0,027	kg CO2 eqcuiv./ m3. Km	0,21
		Subtotal transport	0,47

Figure 13. The component sheet for the pocket spring pocket. For all different components one sheet was made, to enhance transparency and adaptability



	Total transport	Unit	Carbon footprint	Distance (km)	Transport mode	
	Flows					
1	Raw materials	kg CO2 e/ kg	Already included in standard data			
2-3	Semi-finished and finished components	kg CO2 e/ kg	6,73		Truck + trailer 24 tons	0,027 0,084
4	New mattresses - (Auping retail)	kg CO2 e/ kg	1,62		Diesel low-sulphur including combustion	3,7
5	New mattresses (Retail - Customer)	kg CO2 e/ kg	0,34	13,75	Lorry 3 tonnes (m3 km)	0,13
6	Old mattresses (Customer - Retail)	kg CO2 e/ kg	1,07	13,75	Lorry 3 tonnes (m3 km)	0,13
7	Old mattresses (Retail - Auping)	kg CO2 e/ kg	1,54	62,00	Truck 12 tonnes (m3 km)	0,04
8	Old mattress compacted (Auping - Recycler)	kg CO2 e/ kg	0,00	0 | 1080	Truck + trailer 24 (m3km)	0,04
9	Secondary PET (Recycling factory -suppliers)	kg CO2 e/ kg	0,86	*various*	Truck + trailer 24 tons (ton km)	0,084
10	Old steel (Recycling factory - steel recycler)	kg CO2 e/ kg	0,003	5	Truck + container 28 tons net (ton km)	0,072
11	Recycle waste (PET mix)	kg CO2 e/ kg	0,006	48	Truck + trailer 24 tons (ton km)	0,084
		Total end of life	**3,49**			
		Total	**12,18**			

Figure 12. All transport parameters of one life cycle are given on a dedicated page, by the visualized flow network, immediately the effect of a change can be seen

2.2.6 ReCiPe

The first Life cycle assessment started in the 90's of the last century, without clear standardized or structured theoretic methods. The immense and complex spectrum of environmental impacts types, without standardized structure, gave LCA researches a rather vague and unreliable image. In 2000, a group of 50 LCA experts concluded that there was a need for a common framework in which the different types of impact categories are organized, resulting in the ReCiPe methodology.

ReCiPe is a well-known framework to define and categorize impact indicators for life cycle assessments (Hong Dong, Thomas NG). The name ReCiPe refers to the initials of the institutes that innitated and formed this framework: RIVM and Radboud University, CML, and PRé Consultants. Besides, it refers to the noun "recipe", as it provides a recipe to determine the life cycle impact category indicators. According to this method, there are two main levels to derive characterization factors (RIVM 2018):

1. Midpoint indicators have a focus on single environmental issues, such as climate change and human toxicity. These indicators are closely related to the causes of the burdens, for example: "For the midpoint category "climate change", expressed in CO2 equivalents, can be approached by the amounts of emitted greenhouse gasses. Midpoint indicators have the advantage being relatively reliable but might be inadequate for certain forms of decision making. One business challenge example: *"What is the best decision for a company with respect to human beings as whole?" This could be difficult question to answer using midpoint categories. The endpoint indicator 'damage to human health' may be more convenient here.*
2. End point indicators show the environmental impact on three higher aggregation levels, that are:
    a) "*Damage to human health*"
    b) "*Damage to ecosystems*"
    c) "*Damage to resource availability*"

In other words, the endpoint indicators translate the effects of various midpoint indicators into one expression. For example: Mineral resource depletion and fossil fuel depletion do both affect the endpoint category "Damage to resource availability".

Converting midpoints into endpoints simplifies the interpretation and could be supportive for certain decision making. However, endpoint modelling is also assumed to be more scientifically challenging and yield more uncertainty in comparison with midpoint modelling (Jane Bare 2012). For all end- and midpoint indicators, a short description can be found in Table 4. The characterization units are listed here as well, as proposed in the ReCiPe report (RIVM 2017).

2.2.7 Eco-costs: Alternative method

An alternative method to express the environmental impact on products or processes, are eco-costs. The eco-cost give an impression of the amount of money that needs to be invested, in order to compensate the impact on the environment. The eco-cost indicator is an aggregation of many impact factors, such as: human health, ecosystems, resource depletion and global warming. In Appendix 3 the concept of Eco-costs is further explained. In contrast to the ReCiPe indicators that are damage based, eco-costs are prevention based values. In accordance with Auping, there is decided to focus on an impact based analysis (ReCiPe) over a prevention based approach (Eco-costs), in this first life cycle impact study, for various reasons. First, the extended producer responsibility approach seems to focus on the products burdens, rather than the compensation costs. An expression of the impacts may therefore suit the current standings of Auping best.

Impact category	Mid/Endpoint	Characterization unit	Short description
Particulate matter	Midpoint	kg (PM2.5 to air)	Air pollution that causes primary and secondary aerosols in the atmosphere can have a substantial negative impact on human health (Euopean Commision 2013).
Trop. Ozone (Formation) (hum)	Midpoint	kg (NOx to air)	The formation of ozone at the ground level of the troposphere caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO x) and sunlight.
Ionizing radiation	Midpoint	kg (kBq Co-60 to air)	Quantification of the impact of ionizing radiation on the population, compared with the effect of Uranium 235.
Stratos. Ozone depletion	Midpoint	kg (CFC-11 to air)	The destructive effects on the stratospheric ozone layer, over 100 years.
Human toxicity (cancer)	Midpoint	kg (1,4-DCB to urban air)	Is the potential of human toxicity substances emitted to the air, water and soil. Expressed in the dichlorobenzene equivalents per kg of emissions.
Human toxicity (non-cancer)	Midpoint	kg (1,4-DCB to urban air)	Is the potential of human toxicity substances emitted to the air, water and soil, that are not caused by particulate matter/respiratory inorganics or ionizing radiation.
Global warming	Midpoint	kg (CO2E to air)	The emission of greenhouse gas (kg) will lead to a increased global mean temperature. The main greenhouse gasses are represented by CO2E equivalents.
Water use	Midpoint	m^3 (water consumption)	The amount of fresh water used for production. This is especially important for areas where water scarcity plays an important role.
Freshwater ecotoxicity	Midpoint	kg (1,4-DCB to freshwater)	This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.
Freshwater eutrophication	Midpoint	kg (P to freshwater)	Human caused disbalance in freshwater ecology, caused by due to the discharge of nutrients into soil or into freshwater bodies.
Trop. Ozone (eco) (depletion)	Midpoint	kg (CFC-11 to air)	Emissions of Ozone Depleting Substances ultimately lead to damage to human health because of the resultant increase in UVB- radiation.
Terrestrial ecotoxicity	Midpoint	kg (1-4-DCB to industrial soil)	Impact on land organisms of toxic substances emitted to the environment
Terrestrial acidification	Midpoint	kg (SO_2 to air)	Indicator of the potential acidification of soils and water as a result of the release of gases e.g. nitrogen oxides and Sulphur oxides.
Land use/ transformation	Midpoint	m2×yr (agricultural land)	The environmental impacts of occupying, reshaping and managing land for human purposes.
Marine ecotoxicity	Midpoint	kg (N to freshwater)	Impact on sea water organisms of toxic substances emitted to the environment.
Mineral resources (depletion)	Midpoint	kg (Cu)	The depletion of scarce minerals, as e.g. chromium, nickel, copper.
Fossil resources (depletion)	Midpoint	kg (oil)	Indicator of the depletion of natural fossil fuel resources
Damage to human health	Endpoint	Years	Refers to the disability adjusted life years lost in the human population
Damage to ecosystems	Endpoint	Species x Yr	Time-integrated species loss. If species within the system are lost, their habitats have been destroyed or food chain is affected.
Damage to resource availability	Endpoint	Dollar	The effect of human behaviour on resource availability, indicated by the surplus energy (in MJ) required for future resource extraction.

Table 4. Impact categories definitions and units according the official ReCiPe report (RIVM 2017) and the report of the (Euopean Commision 2013)

2.2.8 Selection of ReCiPe impact indicators for this LCA

This is the first study of Auping, that evaluates the complete life cycle of products. Presumably, more analyses will follow in the future. As explained in Section 2.2.6, there are many different environmental impacts to evaluate. Therefore, a decision on what impact categories to focus on the following years, shall be made based on the potential short and long term relevance for the manufacturer and other relevant stakeholders. A multi-criteria decision analysis tool is suggested to evaluate the different impact categories. This tool could be a consistent and transparent option to calibrate the environmental strategy on a regular base. To serve this aim, Auping can use a method that combines two tools, the Analytical hierarchy process method (AHP) and the weighted scorings method (WSM). The AHP method is an analytical tool that can be used to assign certain weights to criteria, by pairwise comparisons. A suggestion for a criteria list is given in Appendix 4. These weights can be used in a WSM method, in which a list (e.g. the impact indicators) are given scores based on expert or management opinions.

For this thesis, all indicators are evaluated briefly by the researcher for Auping's situation. In Appendix 5, a selection of these findings is given. The ReCiPe mid- and endpoint characterization factors and the criteria, were handed to a researcher colleague at Auping. He consulted a group of decision makers of the company, and found scores for the specified criteria. The applied multi-criteria method was similar as suggested in this section, though not completely the same. The most important conclusions were:

- Material depletion and circularity are the main focus points for the nearby future.
- Damage to ecosystems (both marine life and terrestrial life) and human health scored high and should be considered.
- Global warming obtained as well a high score, as it is considered to be an important factor for the society as whole.

Consequently, Auping requested to dedicate this first LCA to the global warming impact. As indicator for the global warming potential of products and processes, often the carbon footprint is given:

"Carbon footprinting is the methodology to estimate the total emissions of greenhouse gases, GHG, in CO2 equivalents from a product across its life cycle from the production of raw material used in its manufacture, to the disposal of the finished product." (Carbon Trust 2007a)

Both at national and international politics, the carbon footprint is a popular instrument to indicate the effect of products, processes or services to the environment. Therefore, in this LCA there will be a great focus on the material flows and energy flows, as these are strongly related to the release of greenhouse gases. In the next section, 2.2.9, this indicator will be more extensively explained.

However, the carbon footprint does not cover the complete environmental impact and risk. Among others material depletion and human toxicity are not considered. Especially, material depletion is a relevant phenomenon for circular systems (Vogtländer 2015), as this is directly related to the need of virgin materials. Therefore, in future research this factor can also be included, to have a more complete indication of performance of the circular mattress.

2.2.9 Global warming and greenhouse gases

The mechanism that causes global warming, can be explained by four steps, see Figure 15. The first step, the release of Greenhouse Gasses, GHGs, can be a result of natural processes or human driven processes. Natural sources of these emissions are organisms, that produce gases for their metabolic processes and other natural processes that involve incineration, such as volcanic activities and natural fires. Human caused GHG emissions are mostly processes that involve incineration, such as non-renewable electricity generation, production processes that require heat, the incineration of waste and transportation by fossil fuels. Livestock can be placed by both categories, as they are a natural creatures that can exist without human interference, while the current proportions of the planets livestock are men made. As a consequence of the release of these GHGs, the concentration of these gases in the atmosphere are rising fast (NOAA 2019). These gases enclose the earth, in a similar manner as the glass of a greenhouse encloses the crops. Therefore, the warmth outflow (radiation forcing) is small compared to the inflowing radiation. The consequence is an increase of the average temperature on earth.

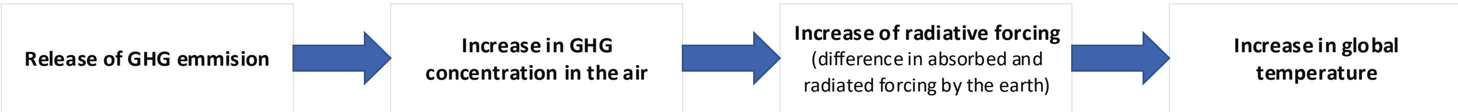


Figure 15. The global warming mechanism, from release of GHGs, to an increased temperature

The GHG results in this report will be reported in *kgCO2e,* carbon dioxide equivalents. More specifically, the assumed "global warming potential" of one released kilo carbon dioxide to the atmosphere. Global warming potential, GWP, defines the heat absorbed by one kilo of a greenhouse gas in the atmosphere, relative to effect of one kilo CO2e. Other greenhouse gases than CO2e, e.g. methane and nitrous-oxide have different global warming potentials than CO2e and are added using specific conversion factors. These multiplicators, often referred to as characterization factors, are complex to determine and can be different for alternative sources. The factors used in this LCA are listed in Table 5 (RIVM 2017). The way this principle works, can be explained by the following example:

The emission of methane gas has an estimated global warming potential that is 34 times greater than CO2e (assuming a period of 100 years). Therefore, for 1 kg released methane gas, 34 kg CO2e equivalents is taken.

The characterization factors assume a certain time horizon of 10, 100 or 1000 years. These numbers are integrated value over this specified period. As suggested by the IPCC, the intergovernmental Panel on Climate Change, a time horizon of 100 years will be used in this study.

Formula GHG	Global warming factor (100 years) (kg CO2e-eq / kg)
CO2E	1
CH_4	34
CH_4 (fossil)	36
N_2O	298

Table 5. Characterization factors as suggested for ReCiPe (RIVM 2017)

2.2.10 ISO Standards for LCA studies

In LCA studies, a rather complex world is modelled by a researcher, by doing simplifications and assumptions. Consequently, the outcomes of a certain research may be influenced heavily by the methodological decisions of the researcher. In order to compare the environmental impact of different product alternatives in a sophisticated manner, a robust framework is required. Two well-established standards for LCA studies are the *ISO 14040* LCA series and the *GHG Protocol/PAS 2050 standard*. In 2018, a new standard is released, with a special focus on greenhouse gasses:

"Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification". (ISO 14067:2018 sd)

This relatively new ISO forms a red line throughout this report. This standard builds further on the principles and guidelines of the well-established standards for life cycle assessments ISOs 14040 and 14044. Figure 18 shows the steps in this framework according to this standard. As already mentioned earlier, in this thesis the relevant guidelines as defined by this standard are provided in blue boxes. For practical reasons, sometimes there is deviated from this standard, both in sequence and content. As already mentioned in Section 2.2.3, the critical review Section *3.1.4.10* (ISO 14067:2018 sd) is not included in this report.

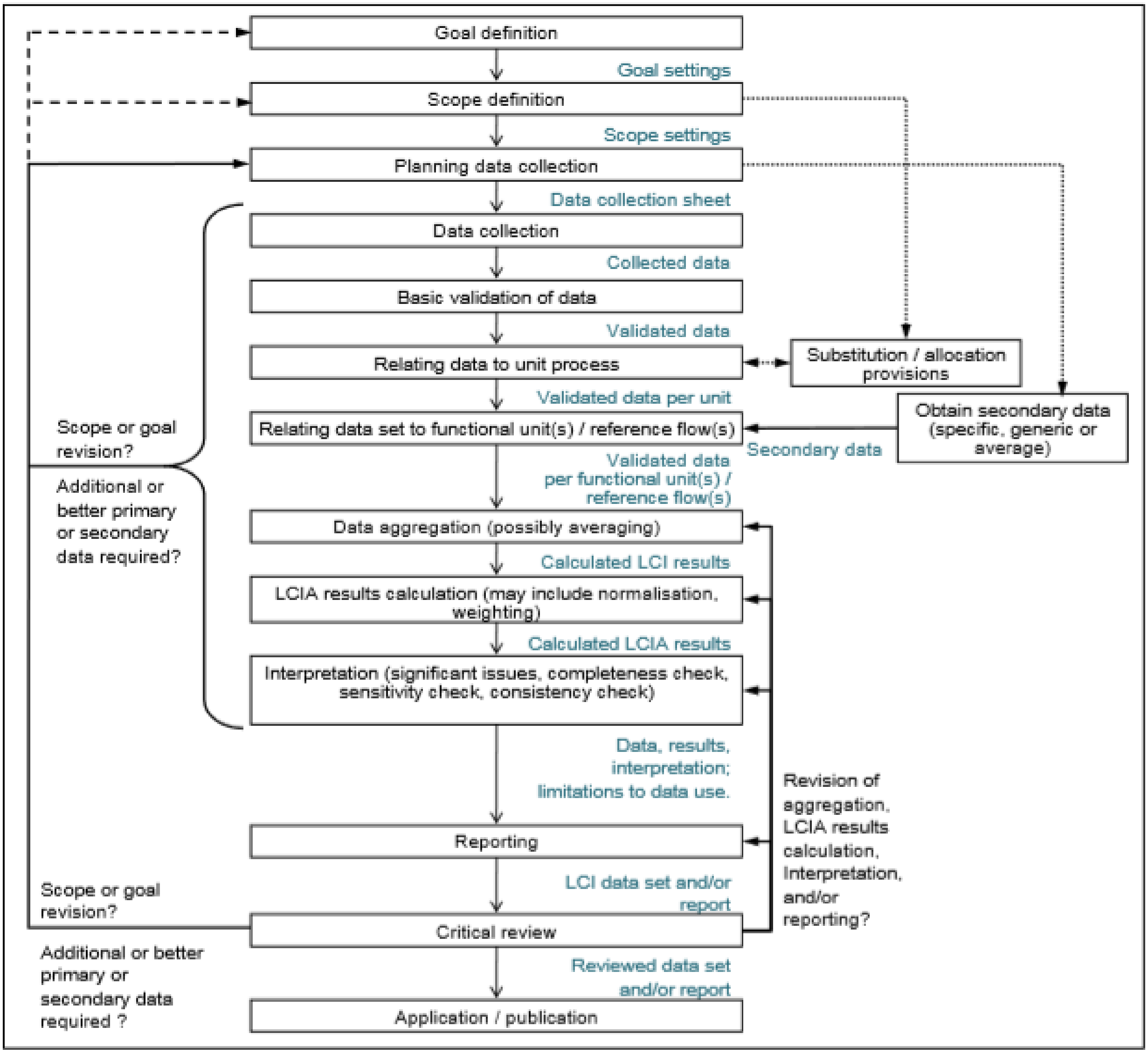


Figure 18. An extensive LCA framework chart with clear iterative character

2.2.11 Conclusions environmental impact research

The following conclusions can be drawn:

- There are various tools to measure the circularity, such as Circulytics, CTI and LCA, that all have another focus and scope.
- In general, a LCA has for phases: Goal and scope, inventory analysis, impact assessment and interpretation. By an iterative approach, there is continuously focused on the processes with the most impact.
- In literature, mattress' carbon footprints between 80 and 160 kg CO2e are known. Importantly, results should only be compared for similar system boundaries and products.
- SimaPro and Gabi are two popular license based LCA tools, that
- The LCA in this thesis is an excel based instance, mainly sourcing data from the Idematapp2020 inventory dataset.
- The GHG oriented LCA standard, (ISO 14067:2018 sd), is used as framework in this LCA.

2.3 End-of-life

In this section relevant theory for the end-of-life phases of both systems are described. First, different end-of-life paths are discussed. Subsequently, the two recycling system concepts of to the mattresses in this LCA, are discussed. Then, various forms of recycling are explained. The recycling efficiency and recycling rate are discussed thereafter. Next, an alternative for recycling, re-use, is explained. In conclusion, other relevant end-of-life-paths are discussed.

2.3.1 End-of-life paths

In every process in the lifecycle of a product, wastes may occur. There are various types of wastes i.e. loss of materials, loss of energy, residual water and by products wastes. A carbon footprint LCA evaluates the emissions caused by a product's life cycle. These are strongly related to the energy and material flows in a system. Material wastes can be divided into two categories:

- Post-industrial wastes
- Post-consumer wastes

Post-industrial wastes are wastes that occur in the production phase. Examples of such are cut-off waste, rejected products and by-products. Post-consumer wastes occur when products are no longer needed by the customer and are disposed. Materials from both origins may be appropriate for recycling. There are various manners to handle material wastes, among others:

1. Landfilling
2. Waste incineration with recovery of heat
3. Waste incineration with recovery of electricity (*discussed in Section 2.3.6)*
4. Chemical Recycling (*discussed in Section 2.3.2)*
5. Mechanical recycling (*discussed in Section 2.3.2)*
6. Re-use *(discussed in Section 2.3.5)*

For this thesis, the relevant end-of-life processes above are discussed in order of relevance in the next sections (displayed for the discussed processes). Figure 19, represents a polymer life cycle for PET, focusing on the waste flows. However, this image can be applied to other polymers that can be recycled as well.

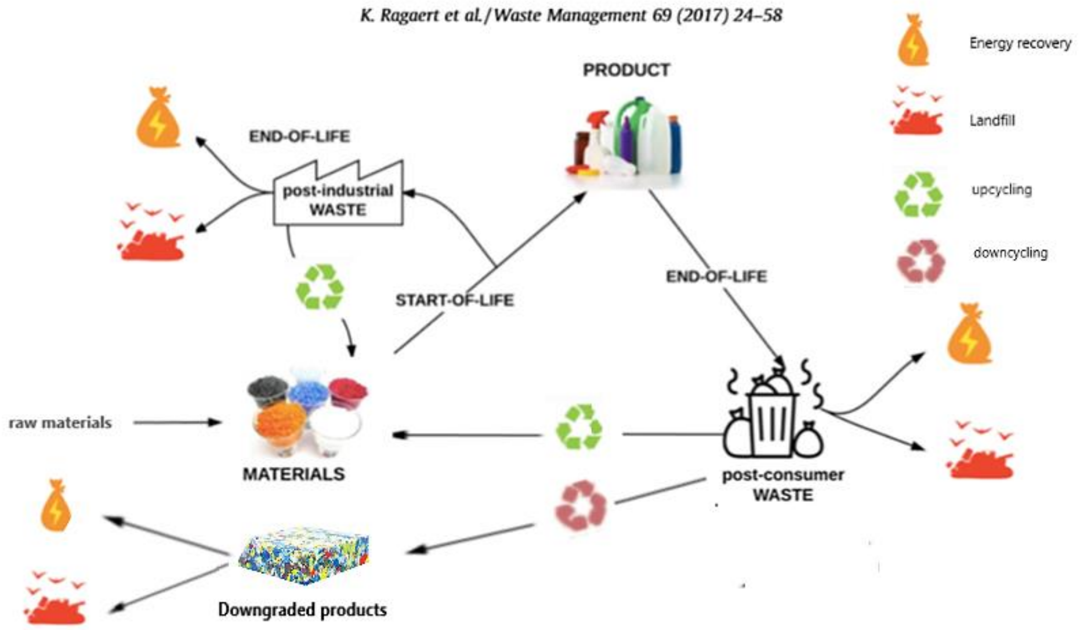


Figure 19. Lifecycle of polymer materials. Depending on the chosen route, polymers will end up in recycling, energy recovery or landfill (Ragaert, 2017). Figure adjusted for this thesis, downcycling and raw material inflow are added

2.3.2 Open and closed loop recycling

In LCAs, a product system can be defined as all processes that are dedicated to the life cycle of a product. According to the ISO (ISO 14067:2018 sd), all process burdens can only be dedicated to one product system in LCAs, to avoid double counting. This is based on the principle that a specific emission of GHGs is released only once to the atmosphere, independent to what product system a researches dedicates it. Recycling creates a connection between different product systems: the end of one life cycle is the start of another life cycle. Annex D of (ISO 14067:2018 sd) provides a systematic approach for this "connection between systems" in CFP studies, by handling it as allocation issue. Recycling cases can divided into two categories: open loop recycling systems and closed loop recycling systems.

2.3.2.1 Closed loop recycling

Closed loop recycling can be defined as:

" Waste material is shunted back to an earlier process in the same system, whereby it directly replaces input from primary production of the same material". (EC 2010)

Herein, the recurring flow has to undergo certain reprocessing steps before it can partially replace the inflow of the original plastic or steel. Figure 20 is a schematic representation of the plastic closed loop recycling concept of the Evolve mattress. In general, only the relatively pure waste e.g. process scrap, or post-consumer materials of controlled origin, are qualified for closed loop recycling. (Rahimi and Garcia 2017). For mixes of different plastic materials, closed loop recycling may be inefficient by the following reasons:

- There can be a great loss of material in this process.
- A significant amount of recycling energy is required, that exceeds the potential benefit of the material recycling.
- After recycling, the quality of the material is worse than the quality of the virgin material. This effect is often called downgrading.

The most well-known use of a closed loop recycling case is that of plastic PET bottles. In many Western countries these are separately collected from other wastes, and recycled into new exemplars. According to (ISO 14067:2018 sd), closed loop recycling can be modelled by formula 1:

$$E_m = E_v + E_{EOL} - R \text{ x } E_v \qquad (1)$$

Where:

$$E_m = \text{GHG emissions tied to raw material acquisition and end} - \text{of} - \text{life operations}$$

$$E_v = \text{GHG emissions tied to extracting or producing the raw material needed for the product, from natural resouces. as if it were all primary material.}$$

$$E_{EoL} = \text{GHG tied to end} - \text{of} - \text{life operations part the product system that delivers the recycled flow (primary system)}$$

$$R = \text{Recycling rate of the material}$$

$$R \text{ x } E_v = \text{Rrecycling rate}$$

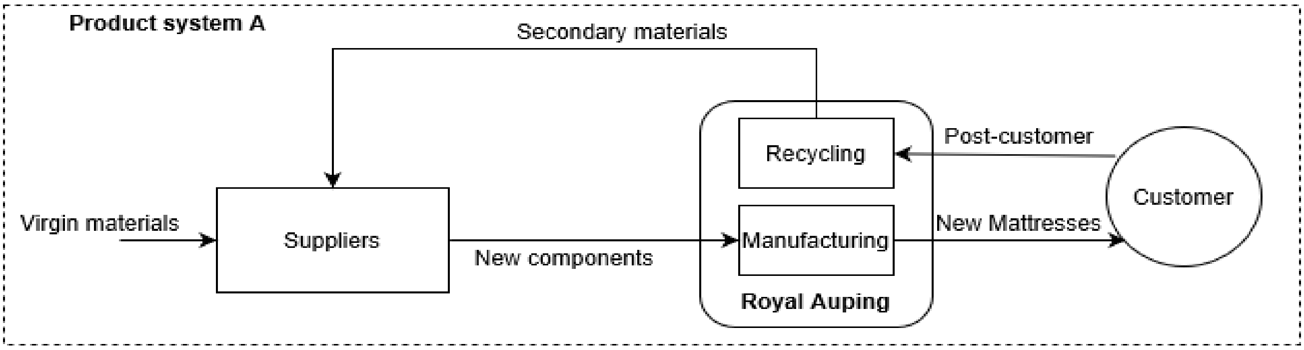


Figure 20. Closed loop recycling system Evolve: "The waste of one production system, can be used as a input for another product system"

2.3.2.2 Open loop recycling

Open loop recycling can be defined as:

The waste material of one product system, will be used by another product system after a recycling process.

This type of recycling is closely related to the concept called industrial symbioses, whereby wastes or by-products become the raw materials, or energy source for another (Ellen Macarthur Foundation 2020). The material that serves the other product system is often referred to as 'the downgraded material', in cases this material is considered of a lower quality. Nowadays applications of downgraded material are e.g. foam insulation products and street furniture. These materials could have served other purposes during earlier lives, such as textile products (clothes, beddings) or foam based products (fillings of furniture). In general, insulation foam products have less strict aesthetic and physical requirements, as its function is mainly preventing heat or cold flow between different spaces without being visible. Therefore, for these products there is often less need for a strict uniform material composition, with an even distribution of paint. As a result, the market price of such downgraded material is often significantly lower than the original material market price. Especially if the market volume of downgraded content increases, the value of this secondary material may decrease. The effectiveness of this type of recycling may be debatable for certain cases: if there is no demand for the recycled content, this recycled material can still be considered being waste. Thus, one important principle for purposeful recycling is, that the recycled material replaces the need of virgin content.

Figure 21. Example of recycled material that has less strict physical and esthetic characteristics for the new product

In Figure 22, a simplified representation of the open loop recycling of the Vivo mattress is given. To avoid double counting of environmental burdens (a emission is only released once) , the processes should be allocated.

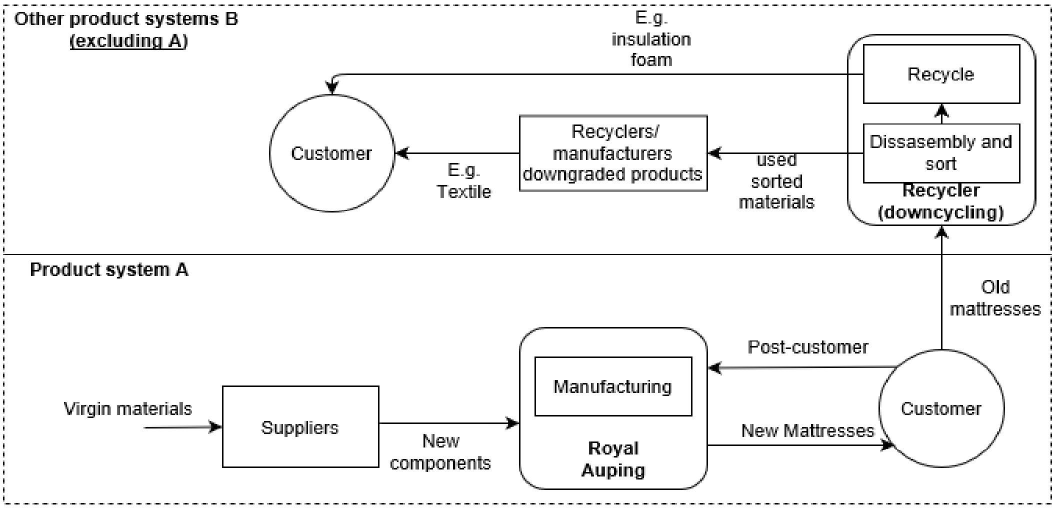


Figure 22. Open loop recycling system: Recycled material is used by another product system B

There are various manners to allocate the burden of processes in the shared production system. One example:

The Recycling process of product A (that of the mattress), is used as material source for product B (that of insulation foam). These recycling GHGs can be fully assigned to product A (as end-of-life process), fully to product B (as material inflow process), or partly to both.

This allocation is a great source of discussion among researchers, as these choices can affect the result significantly. Therefore, in this LCA, three different scenarios are evaluated for the allocation of the recycling process. These can be found in Section 4.6.

2.3.2 Two types of recycling: Mechanical and Chemical recycling

There are two current pathways of recycling of polymers that differ significantly in process: chemical and mechanical recycling (Ragaert 2017). Both versions will be discussed in this section.

2.3.2.1 Chemical recycling

In literature, there are various recycling processes that are referred to as chemical recycling. Two forms discussed in this section are chemical depolymerization and pyrolysis.

Chemical depolymerization

For the first form, polymer fibres are brought back to monomers (depolymerization), whereafter the material is repolymerized (Fletcher 2008). This is only possible for a limited group of plastics, amongst others various PET and EPS polymers. For textile cases, this secondary granulated material could be brought to a spinneret to produce new yarns. This is shown in a simplified manner in Figure 23.

This chemical recycling process is not commonly applied on an industrial scale, as the current methods require significant energy inputs. (García 2017). However, various experts say that chemical recycling may only become feasible on a large scale, as higher efficiencies may be expected by scaling up. Furthermore, only one polymer can commonly be restored to virgin quality from the mix inflow materials. There are various initiatives that claim to perform this type of recycling on a small scale, such as the Dutch companies Cumapol, Senbis and Ioniqa. The latter developed a method to depolymerize PET and to process it to 'virgin quality' pet. According to this company, this process works as follows:

"The plastic, also known as a polymer, is submerged in a solution, such as water or glycol. The molecular structure of the polymer, which consists of identical units (the monomers), will then slowly start to dissolve. With the raw material we harvest, we produce new, clear PET bottles that are food safe." (Ioniqa 2020)

Once pure monomers can be derived from polymers efficiently, the material prices will not be dependent on oil price fluctuations anymore (García 2017).

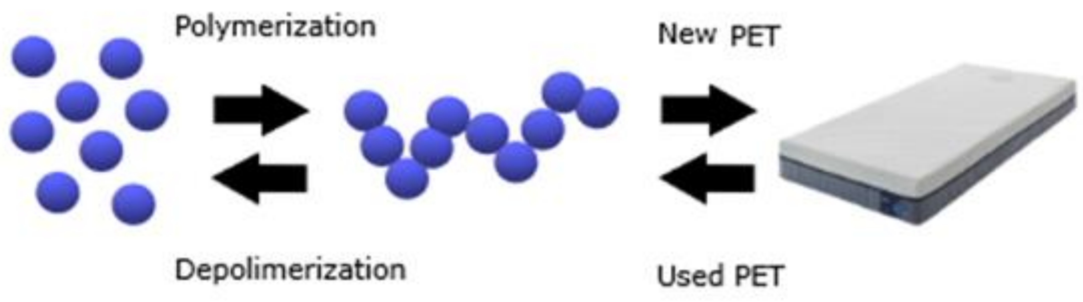


Figure 23. Schematic view of the processes of depolimerization. The blue dots represent monomers

Pyrolysis

The other form of chemical recycling is pyrolysis. Hereby, plastics are subjected to high temperatures (400-600 degrees) (Kaminsky and Scheirs 2006), using a catalyst, which may be utilized in a vacuum. Pyrolysis is most promising for polyolefins, e.g., PE and PP. (McKinlay 2019).

Relevant points to consider for chemical recycling for this LCA are:

1. For mixes of plastics in chemical recycling, often the process temperature will be chosen at the melting temperature of the highest melting component. This may potentially lead to overheat and degradation of lower melting components. (K. Ragaert, 2017)
2. Chemical recycling of plastics is yet not applied on an industrial scale. Processing methods should be simple and low energy intensive for feasible business models. (Rahimi and Garcia 2017)
3. The discovery of catalytic methods for the chemical recycling of polymers, that are operative under relatively low temperatures, may be a promising for chemical polymer recycling on a larger scale. (Rahimi and Garcia 2017)

2.3.2.2 Mechanical recycling

At mechanical recycling, waste materials are transformed into 'new' raw materials without altering the basic structure of the material. (European Bioplastics 2015). Hence, this method does not try to bring polymers back to monomers, but rather focusses on re-using the existing polymer structures. Mechanical recycling can be done either in open or closed loop form. The companies Mattress Downcycler and Matras Recycling Europe are open loop examples, where from remainders of mattresses various products are made e.g. insulation foam and secondary textile fibers. The outflow products may have different purposes and qualities* in comparison with their former functions. Mixes of different materials are separated only to a limited extent, whereby the output flow (the secondary product) contains a variable mix of materials and thus qualities. For this downgraded form of recycling, the following points are relevant to address:

1. The composition of the outflow may be of fluctuating composition and quality, as the inflow may only be to a certain extent controlled (mix of various mattresses).
2. After the lifespan of the secondary material, recycling is in general not possible and the remaining material related energy will be lost.
3. The production of secondary material shall be in line with the market demand. If this is unbalanced, a surplus of un demanded secondary material may be the result.

One well-known example of closed loop PET recycling is that of PET bottles, present at various countries in Europe. This process is already shortly discussed in Section 2.3.2.1. Within this take-back-system, often regulated by the government, bottles are being collected and reprocessed to new bottles. Most PET closed loop recycling examples in literature refer to this specific process.

The following processes are frequently used in mechanical recycling:

- *Collecting and sorting*: The material is collected, either of post-industrial origin, or post-customer origin.
- *Shredding*: The sorted materials, are cutting in smaller pieces, to make further handling practically possible and obtain a more homogenous extruding inflow composition.
- *Agglomeration*: Hereby, the plastic is compacted by heating and shrinking.
- *Extruding*: The material is heated, melted and pressed through an extruding column. The output flow is a flow of liquid plastic. Meanwhile, the material is pressed through a specifically selected filter, that ensures larger filth particles to be blocked.
- *Granulating*: The flow of liquid plastic is brought to pellets, also referred to as pelletizing.
- *(Solid-state) Polycondensation*: An optional step in the recycling process. By this process, the intrinsic viscosity can be rebuild in a tumbling dryer or vertical tube reactor (Cumapol 2020). Besides, high humidity filth levels in the granulate can be extracted from the material by this process. The result is an outflow of granulate, that meets the desired specification.

After any of the above mentioned mechanical recycling, this new granulate can be processed by a spinneret, to process new yarns. The energy required in mechanical recycling strongly dependents on the melting temperature of the inflow materials. For PET, this temperature is 245-265 degrees Celsius, depending on the exact composition of the PET material (Selke 2001).

Several relevant aspects regarding mechanical recycling are:

1. In general, only controlled pure flows of material, e.g. of process scrap or post-consumer materials of controlled origin, qualify for closed loop systems. (Rahimi 2017)
2. The products physical properties may slightly decrease after each recycling loop. Relevant characteristics are the intrinsic viscosity and tensile strength, that may both lower in value for every recycling instance (Frounchi 1999). PET and PVC are materials well known for its good recycling potential, with relatively small material quality degradation and high process yields.

2.3.3 Recycling efficiency & recycling rate

Whether recycling is an effective end-of-life path for a product, depends on the recycling efficiency of the system. In this thesis recycling efficiency is defined as the GHGs caused by recycling against those spared by recycling.

- *Burdens:* The GHGs burdens are related to the recycling process and the transportation of the materials for recycling.
- *Savings:* The GHGs savings are related to the production of the virgin material, that is replaced by the secondary material and the prevented GHGs for waste processing.

The recycling efficiency depends largely on the recycling rate of the system. There are various definitions of the recycling rate in literature. In this thesis the recycling rate is defined as:

'*The ratio of recycled materials versus the waste generated* (M. Haupt 2016)'.

The recycling rate of a system is affected by various factors, such as:

- *The compositional complexity of the inflow material mix:* In general, products that are composed only one material, so called "mono-materials", are more compatible to recycling.
- *The material efficiency of the used machinery:* Not all material that flows in the recycling machine is effectively processed, a part of the material will become waste. This is often the first material that is recycled in a shift, or the remainder in the machine at the end of a shift (Starlinger 2020).
- *The requirements of the output flow (purity, physical characteristics):* The quality requirements of the output flow, defines the amount of virgin material that should be added to the mix[6] or what further processing is required, to obtain the desired material characteristics.

2.3.3.1 Intrinsic Viscosity: I.V factor

One of the most important characteristics of PET is called the intrinsic viscosity, or IV (Thiele 2007). A higher IV value implicates longer polymer chain lengths, which results in a more viscose material. This value decreases over the products lifespan and through the recycling process. Depending on the desired application, a certain intrinsic viscosity is needed:

- Fibre grade: 0.40 – 0.70 - textile
- Bottle grade: 0,70- 0.85 plastic bottles

(Gupta 2002)

If the IV of the output material is not at the required level, it can be increased by blending virgin PET or with Solid State Polymerization[7]. For Auping, this IV value will be an important factor to analyse during recycling tests. Another factors important for recycling is the humidity level, as polyester is an absorbent for water.

2.3.3.2 Recycling rate in literature

Auping is a first mover for closed loop recycling in the mattress industry. Therefore, literature on recycling can be useful to estimate the recycling rate in this LCA. According to (Starlinger 2020), most recycling cases (mostly packaging recycling) with its machinery, yield a recycling rate of 96%-

[6] Strictly taken, the recycling rate as defined earlier on this page, is not affected by the addition of virgin material if no extra waste is generated.
[7] In this thesis sometimes also referred to as poly condensation

99%. However, mechanical recycling of textile and especially mattress textile is assumed to differ significantly, so it can only be interpret as rough estimate for this recycling case.

In literature, mostly all cases of the closed loop PET recycle concern plastic drinking bottles. These cases cannot be compared fully to the closed loop recycling of the Evolve for various reasons:

1. Bottles are intended to contain nutrition. The health and safety requirements for these products are very strict. Mattresses are as well intended for daily use, with physical human-product contact. Therefore, health and safety aspects are still of great importance, but the requirements are less strict then for bottles.
2. The required IV factor is most likely higher for bottles, than needed for mattress textiles (Auping 2020).
3. The levels of contamination of the disposed goods at the material inflow are not similar for both systems either.

For these reasons, bottle recycling case studies from literature can be used somewhat indicative, but are not completely representative for this closed loop mattress recycle study. Consequently, the recycling rate and energy requirements are as much as possible based on the early test results and less based on available literature.

2.3.5 Re-use

The materials in a product that have a significantly longer life-span than the product itself, can possibly apply for an alternative end-of-life solution: Re-use. In this thesis re-use is defined as follows:

Products or parts of products that have a secondary life, without significant reprocessing.

Figure 24. Lansink's waste hierarchy ladder

The terms refurbishing and re-using are used interchangeably these days, for this phenomena. From a sustainable perspective, re-use ranks higher than recycling, since less additional energy is required for reprocessing, and more material is conserved. Various frameworks such as Lansink's ladder and the butterfly model of Macarthur, describe re-use as the better alternative for recycling, see Figure 24.

For the circular Evolve mattress, the steel springs have an estimated life span that exceeds the products life significantly. An important indicator for the spring material quality, is the expanded height. A research requested by Auping on the quality loss of its steel springs, indicates that after 30 years a height reduction of 1.6% can be expected and after 55 years 1.9% only. This is a strong indication that the springs apply for high quality re-use. Presumably, for re-use several additional steps are required to ensure that Auping's quality standard is met. This is can be a ground for further research. However, in this LCA, the carbon footprint for various spring re-use rates are evaluated. The re-use rate is defined as:

'The amount of re-used springs in a mattress, divided by the total amount of springs'.

Additional process such as a quality checks and a cleaning step, are not yet known. For the scenarios in this LCA, these process are assumed to be negligible.

2.3.6 Landfilling and waste incineration

All waste materials that are not re-used or recycle, are either landfilled, or follow a certain waste processing path. What processes are commonly applied, differs significantly between Western European countries and other parts of the world. In the US, landfilling is the most likely end-of-life path, that accounted for 53% of the solid waste in 2015 (Donahue 2018). Hereby, materials that are considered to be at end-of-life, are collected on a large dump of garbage. For over a quarter century, the Dutch government employs a landfill reduction policy. As a result, the amount of waste landfilled, makes up less than 3 % of the waste total (Scharff 2014). In western-European countries, including the Netherlands, the most standard end-of-life treatment is municipal waste treatment (Ecocostvalue 2020). Hereby, the metals are extracted from the waste flow and recycled (open loop), the remaining flow that holds plastic, textile and wood is incinerated with electricity recovery. In this LCA, waste incineration with energy recovery is assumed to be the standard end-of life treatment for all waste flows that are not recycled.

2.3.7 End-of-life conclusions

In summary, the following end-of-life conclusions can be drawn:

- There are different end-of-life paths for products, such as: waste incineration, re-use, various forms of recycling and landfilling.
- From a sustainable perspective, re-use is the most efficient end-of-life path for disposed products.
- Most material waste in The Netherlands is incinerated with partial recovery of the material energy. In contrast to other countries, landfilling is hardly ever applied in the Netherlands today.

Furthermore, the following recycling conclusions can be drawn:

- Two forms of recycling are chemical recycling and mechanical recycling. At chemical recycling, molecules are brought back to monomers. At mechanical recycling, material is melted, filtered and formed into raw material, such as PET pellets.
- Chemical recycling is proven technology on small (laboratory) scale, rather than on an industrial scale. Two forms of chemical recycling are depolymerization and Pyrolysis.
- Mechanical recycling is in general the more energy efficient process. As a consequence, it is proven technology on a large scale, for various applications such as bottle-to bottle recycling and disposable plastic bags.
- Closed loop recycling of mattresses, so called mattress to mattress recycling, it is still in a pioneering phase of development.

3. Goal and scope

As mentioned in the previous chapters, the LCA structure underlies the structure of this thesis. In the first phase of LCAs, the research structure will be set by defining the goal and scope.

The models and methods that will be developed during this research, should provide Auping insights into the potential environmental benefits of the circular mattress. Preferably, the results of the study are accepted by both customers and external parties as relevant measurement of the product environmental impact. Hereby, the system boundaries are crucial for a relevant study outcome. Therefore, the decisions made in this chapter should always be taken into account, during the interpretation of the study outcomes.

The following sub-questions are answered here:

- What systems are studied?
- What functional unit is used to express the results of the study?
- What system boundaries are set for both systems under study?
- What allocation procedures are used?
- How is the data collected?
- What quality requirements are set?
- How is the data quality guaranteed?

3.1 Goal of the Carbon Footprint study

First the goal and intended audience of this LCA are discussed. Then, the scope of the study, including the system boundaries and cut-off criteria are given. Subsequently, some specific requirements for comparative LCAs are evaluated. Lastly, data quality is discussed.

3.1.1 Goal definition

The goal of the LCA is in line with the overall thesis, as defined in Section 1.4 of this report and yields:

"Compare the global warming impact of a circular mattress, with a conventional exemplar"

As explained in Chapter 2.2.9, the environmental impact will be expressed by the products' carbon footprints.

3.1.2 Intended audience

The results in this thesis can be used by Royal Auping for decision making purposes and for internal communication. The results cannot be compared directly with results of other Life cycle assessments studies, as different cut-off criteria and modelling decisions may be made. Specific results shall not be communicated as absolute truth to external parties (e.g. consumers, suppliers), since results in these kind of studies commonly have a higher degree of uncertainty.

3.2 Scope of the study

According to the (ISO 14067:2018 sd), the scope of the study shall include all components in the non-dashed boxes of Figure 25. The critical review is denoted as optional and is not included in this study.

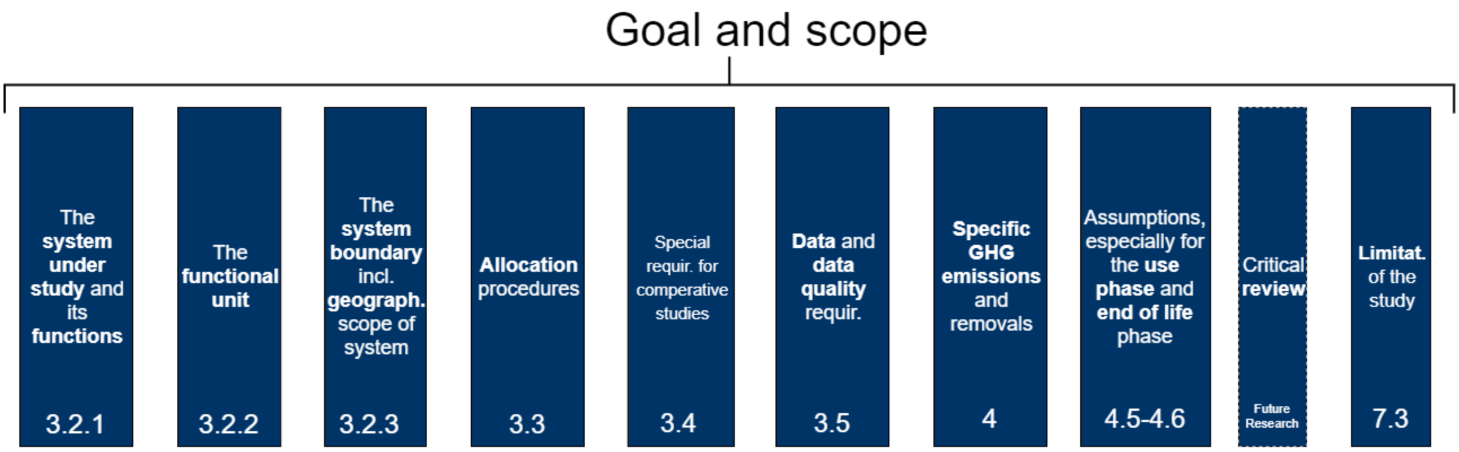


Figure 25. All elements that should be in a goal and scope according to (ISO 14067:2018 sd). The critical review is not included in this thesis and may be a ground for future research

3.2.1 System under study and its functions

3.2.1.1 Definition mattress

A bed mattress can be defined as follow (Oxfort 2018) :

"A fabric case filled with soft, firm, or springy material, used for sleeping on."

The product group "bed mattresses" consist of a great variety of mattress types, such as foam based, latex mattresses and spring interior mattresses. This research only consider the latter: ***Spring interior mattresses manufactured by Auping.***

According to the (RAL-GZ 441/2 sd) standard, spring interior mattresses can be defined as:

"*Removable cushions for resting and sleeping furniture, of which the performance on support and elasticity is principally caused by the core of the spring core.* "

3.2.1.2 Composition of Mattresses

The composition of mattresses is defined by two major components: the core and the ticking. These can be described as follows:
- **The Core**: The inner part of the mattress that provides the user support. The differentiation between the different mattress categories 'foam mattress' and 'interior spring mattress', is mainly related to the type of core used.
- **The Ticking**: The outer cover of the mattress, that provides a comfortable and protective top layer around the core. This cover can often be rinsed, either in a washing machine or through dry cleaning.

In this research, two mattresses are compared that both have interior spring cores.

3.2.1.3 Mattresses in this study

In this research the life cycle impact of two products are compared, the conventional mattress 'Vivo' and the circular mattress 'Evolve'. The Evolve is introduced as environmentally improved version of the conventional mattress product lines of Auping. The Vivo mattress is chosen as conventional alternative in this research. The Vivo mattress is the high end mattress line of the Auping product base. Indicated by the first researches initiated by Royal Auping , the Evolve mattress has good potential based on the product material composition, to become this eco-friendly alternative. However, an elaborative analysis of the life cycle of the both products is required to approach environmental impacts of both products.

3.2.1.4 Product specification

Each mattress line of royal Auping consists of various models. These designs differ in size, hardness and material choices. In Appendix 24 , all options for the Vivo and Evolve mattress are listed. For the Vivo mattress only, there are 576 different configurations possible. To make a fair comparison, the two mattresses that will be evaluated should be most similar in functionality and characteristics for both product lines. The specific types of mattresses used in this thesis are chosen arbitrarily. However, the size and characteristics are seen as standard size and the typical showroom model of both mattress lines (Auping 2020).

3.2.1.5 The specific mattress types

The Vivo mattress, with 90*210 cm size, medium hardness, breeze ticking, and a comfort layer made of latex, is chosen to represent the conventional product in this research. According to the bill of materials, this mattress consists of 49 different components. Over the recent decennia, the Vivo mattress had various version releases, that are to a great extent similar. However, they differ slightly in composition, as a result of version updates. For this research, the early 2018 version of the Vivo mattress line is chosen. The decision for this version is not expected to influence the research outcome significantly, as only minor changes in material composition and suppliers took place over the last two years.

The Evolve mattress, with 90*210 size and medium hardness is chosen as circular mattress product reference in this thesis. According to the bill of materials concept version early 2020, this mattress has 26 different components. This bill of materials, see Appendix 23, is used as base for the circular model. As this is a relative new mattress, first released in May 2020, only a few differences in composition are expected for the final release.

3.2.2 Functional unit

3.2.2.1 Functional unit definition

In a life cycle analysis, the basis for the calculation of environmental burden is called the functional unit (G. Jonker 2012), abbreviated as FU. The functional unit can be described as follows:

"The functional unit helps you compare the overall environmental performance of different product systems in terms of impacts per unit of delivered service." (Sustainable minds 2020).

The primary purpose of the functional unit is to ensure compatibility of LCA results and to provide a reference to which the input and output data can be standardized (Deliege 1995). Depending on the research goal and scope, the functional unit may be different expressions. Two examples:

- For the comparison of different light bulbs, the FU can be:
  One light bulb that delivers 20000 lumen during 4000 hours.
- If the environmental burden for various office seating solutions is evaluated, the FU can be:
  High quality seating for employees for the use of ten year.

Two relevant aspect to consider while defining the functional units for product comparisons are:

- The two products have a similar functionality
- The two products shall have a similar lifetime (use lifespan)

As a consequence, in this research the following function unit is used:

A single person mattress of 90 x 210 (w x l) used daily, for a period of 10 years.

Functional unit:

The reference unit through which a system performance is quantified in a LCA.
(ISO 14040:2006 sd)

3.2.2.2 Justification of the FU choice

Both mattresses in this research have an identical functionality: Products to lay on while sleeping, providing comfort and support. Besides, the average lifetime of both mattresses is assumed to be equal as well, 10 years of use. According to Auping, the mattress degradation process mainly takes place in the use phase. Auping production process is fully make to order, following the Kanban principles, by an target delivery time of two weeks (Auping 2020). Therefore, it is unlikely that product degradation takes place during storage. Before usage, the mattress is always transported in a protective plastic bag, which prevents dust and dirt contact with the mattress in the distribution process. For these reasons, the start of the products lifetime and the degradation process, is assumed to be at the collection of the customer.

3.2.3 System boundaries

3.2.3.1 VIVO system boundary

For the conventional mattress, the VIVO, the system boundary is cradle to grave. This implies that all steps in the products life span are considered in this study, from material extraction, until the material's end-of-life. However, the end-of-life phase of the VIVO, in which a part of the material is recycled in a downgraded manner, involves a shared product system. In other words, the recycling of material can also be seen as first step of the life cycle of the secondary products (e.g. the insulation foam product). Hereby, the system boundary is set after the recycling process, but before the production process of the secondary product. Figure 26 shows the simplified Vivo system diagram with its boundaries for this study. Product system A is the VIVO system, and the dashed area with 'overlap in systems' denotes the shared processes with other systems. Only product system A and the 'Overlap in systems' part is included in study. The upper dashed box concerns only other product systems and is therefore assumed to be out of this system boundaries. The ISO (ISO 14067:2018 sd) describes various methods to include the contribution of the downgraded material to the carbon footprint of the primer product. These different perspectives can be found in Section 4.6. Figure 6 in Chapter 2, shows a more elaborative diagram of the VIVO system.

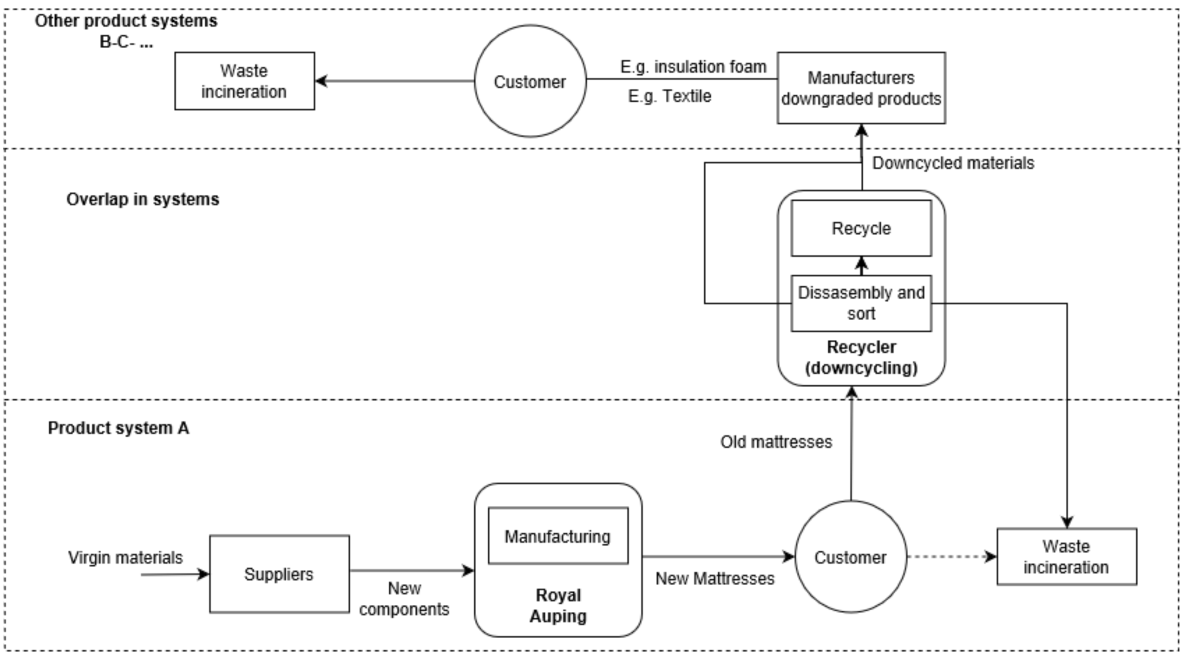


Figure 26. The open loop system of the Vivo. The end-of-life processes are part of the debate; can be part of A or B-C

3.2.3.2 Evolve system boundary

The Evolve system can be defined through two different perspectives: cradle to grave or cradle to cradle. The cradle to grave perspective puts more emphasis on the flow of waste that is not being recycled (1 – recycle rate). For the cradle to cradle perspective, the name refers to the recurring flow within the system. Due to the expected high recycling rate of the PET, cradle to cradle suits the Evolve mattress system best. Figure 27 is a schematic representation of the non-steel part of the circular system. It is not clear yet what specific recycle steps will be performed by whom: Auping or collaborating companies. Therefore, the analysis is done for various scenarios.

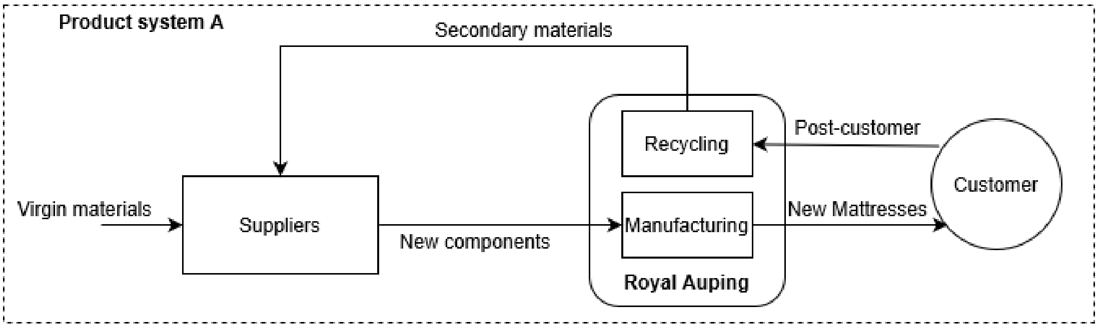


Figure 27. Evolve: Closed loop recycling system for PET

However, the steel springs in the Evolve mattress follows a different path. A part of the springs may be re-used directly after certain quality checking and upgrading steps. The remainder, is after use adopted by the local organized steel recycling system. See Figure 28.

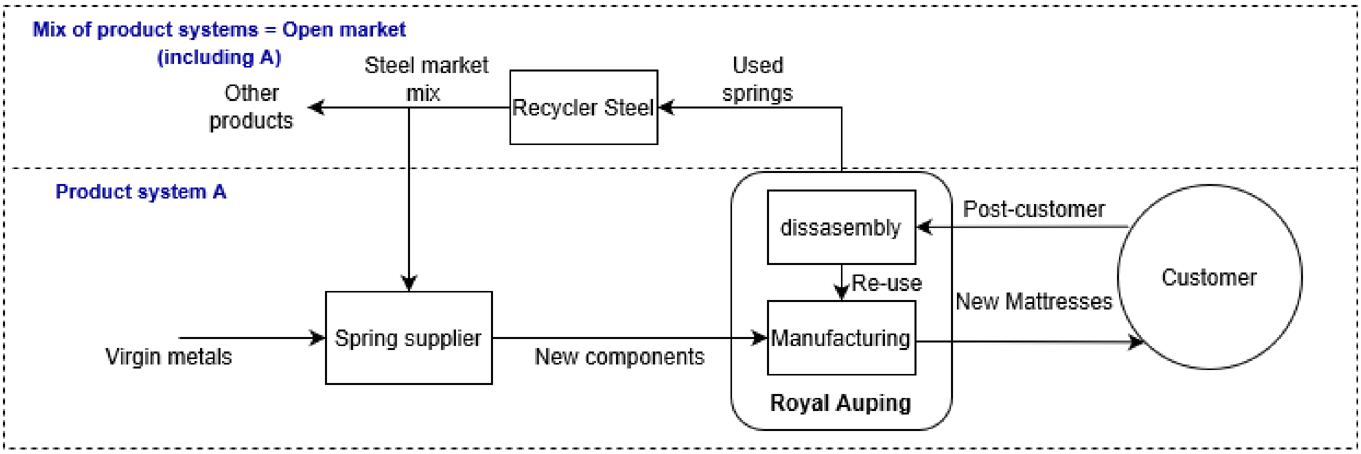


Figure 28. Evolve: Open loop recycling of steel

3.2.3.3 Cut-off criteria

Cut off by weight

The bill of materials are used to determine the materials, components and quantities in this study. However, for practical reasons, all components that contribute less than 1% to the total mass are cut-off. The result, a component lists of 17 and 11 components, can be found in Appendix 23. In Table 6 and 7, the remaining percentage of weight per mattress is given. In order to have a realistic estimate of the total carbon footprint per mattress, these values are normalized for the cut-off waste:

If the obtained carbon footprint of the Vivo is 95 kg CO2e, this value is represents only 96% of the weight of this mattress. After normalization, the estimated carbon footprint is 95/0,97 = 99 kg CO2e.

Vivo	
Percentage of total weight included	97%
Number of components	17

Table 6. Weight based cut-off Vivo

Evolve	
Percentage included of total weight	99%
Number of components	11

Table 7. Weight based cut-off Evolve

To be sure that no critical materials are cut-off by this restriction, all other components are evaluated briefly. As a consequence, the adhesive of the Vivo mattress is also included, so that the adhesives of both mattresses are included in the study.

Cut-off carbon footprint

All known emissions should be included in this LCA. However, for most processes this data should be collected, which can be an intensive process. For practical reasons, all process data that is not easily available and is assumed to contribute less than 5% to the total carbon footprint, is cut-off. In general, the production processes that require a significant amount of heat, are responsible for a large share of the emissions. In the U.S. industrial heat accounts for two-thirds of the total carbon footprint (IEA 2018). Therefore, a special focus is put on these processes.

3.2.3.4 Geographical scope

The size of the environmental burden of materials and processes depends relatively strong on the geographical location. Influencing factors are: the energy sources used (e.g. sustainable energy, grey electricity), the efficiency of processes and the transportation distances. The manufacturer of the Mattresses, Royal Auping, fully operates from its production location in Deventer. The locations of the relevant suppliers for this LCA, are listed in Appendix 16. The majority of the direct suppliers are located in Western Europe, which is part of the integral strategy of Auping, regional sourcing. As a consequence, the Idematapp2020 database is used as generic data source; that is Western-European oriented. However, potential sub-suppliers are to some extent not fully traceable, either for confidentiality or practical reasons.

The products of Auping are distributed over more than 10 countries. The largest markets for Auping are The Netherlands (+/- 50%), Belgium, Denmark and Germany (Auping 2020). The end-of-life phase of other countries differs significantly from the Dutch situation, as well the transported distances. For practical reasons, mattress distribution outside the Netherlands is not included in this study. Therefore, the results of this thesis are only applicable to mattresses sold in The Netherlands.

3.2.3.5 Waste flows

Production processes can yield a certain material loss or waste. All material losses in the production processes effect the carbon footprint of the final product. Therefore, for each process an estimation of the material loss must be made. About production flow within Auping, a good estimate of these wastes can be made. For most other process controlled by external parties, less accurate and more incomplete waste data is available. For specific process characteristics, materials types and general information about the companies, this material losses is estimated.

3.3 Allocation procedure

3.3.1 allocation situations

In LCAs each energy burden should only be counted for one product system. Therefore, commonly LCA studies require allocation procedures to deal with energy and materials that are shared by various product systems. According to ISO (ISO-14044:2006 sd), these "allocation factors" partition the input and output flows of processes between different production systems. One example related to this LCA:

> *In the textile factory of Auping, various types of textile products are produced. Such as, cushions, mattresses and mouth masks. In order to find the energy required to produce one mattress, this energy share needs to be derived from the total energy of that factory by* ***allocation factors****.*

In life cycle assessments allocation factors may be required for various purposes, e.g. the allocation of transportation burdens, the distribution of energy of end-of-life processes between products and the energy of production processes between different products. In this thesis, allocation of energy is applied for the following situations, to define:

- **The share of the yearly energy usage in the Auping factory, dedicated to this specific mattress type.** (See the example described above)
  At this production facility, a great variety of products is produced. The energy monitoring of the factory is organized per department, rather than per machine. At each department of the factory, various products and product versions are produced. Monitoring the real time energy usages of each machine, is assumed to be practically infeasible for Auping. Therefore, the energy required to produce one mattress, can only be obtained by allocating a share of the monitored energy usages, to the production of one mattress.
- **The allocation of energy of supplier processes**. Various suppliers involved in the systems under study, provided energy data for the production of its components. For suppliers that produce only one product type on the involved machinery, there may be no or limited need for allocating. For all other cases, the supplier itself made an estimation of the energy allocation between products in this LCA.
- **The allocation of the end-of-life processes of the VIVO mattress**, between the "parent" product, that delivers the waste material, and the "child" product, the secondary life of the material. Downcycling is a debatable allocation issue. The recycling process burden can be seen as first step of the child product life cycle, or as end-of-life process of the parent product, or may be allocated between both product systems. For a more detailed insight see the next section.
- **Transport allocation**, if the space of the vehicle is shared by more than one product group. In practice, trucks or other transportation modes that transport goods, often carry a load that is a mix of different products. In order to approach the transportation burden for one product, allocation factors that relate to the volume or mass usage of the vehicle, are used.

The stepwise procedure as proposed by ISO (ISO 14067:2018 sd), is used for situations that require energy allocation in this thesis. This procedure is as follows:

1. Whenever possible, allocation should be avoided by:
    - Deriving the shared processes into smaller processes that only involve one product type and collect the data for these.
    - Expanding the product system by the other products.
2. If allocation is applied, the inputs and outputs of the process shall be partitioned in a way that reflects the physical relationship between the different products.
3. If the physical relationship only is no proper ground for allocation, other relationships may be used for allocation. Such as, economic allocation (the value of products), or the production time (without idle time) required to produce the products.

For the uncertain cases in which allocation is not based on quantitative underpinning, the impact of this allocation is evaluated for various scenarios. Hereby, the effect of different allocation factors on the total carbon footprint is evaluated. In Table 8 the used approach in this LCA is described, for all situations that required allocation. For some of the energy inputs, the deviation of energy shares is based on experts knowledge, rather than clear physical relationships. Improving this allocation estimation may be a ground for further research.

Situation	Allocation based on	Method
Manufacturing at Auping	Physical characteristics, expert opinion	The energy consumption of each department is allocated to the specific mattress under study (the FU), by the best estimate of an expert or based on physical characteristics
Suppliers	Not known	The energy allocation to products is estimated by the expert of the supplier. The allocation method is not known
Allocation of end-of-life Vivo	End-of-life processes = primary product End-of-life processes = secondary product	The allocation of the end-of-life processes are evaluated by various scenarios, as there
Transportation	Volume/weight contribution transported goods	Depending on the density of the transported goods, either the mass or volume of the transported goods is used for allocation.

Table 8. The allocation situations in this LCA given, with a short discription of the allocation method

3.3.2 Allocation for end-of-life processes, Open loop recycling.

Open loop recycling, the waste of one product system is used to serve another product system, requires special attention. As already mentioned, the recycling of the Vivo mattress, is an example of this type of recycling. From a life cycle perspective, open involves two product systems:

- The "parent" product system, that delivers the waste material (The Vivo mattress)
- The "child" product system, that receives the waste material (E.g. the insultation foam)

The end-of-life processes, such as disassembly and recycling, may be either seen as final step of the so called "parent" product system, or the first step of the "child" product system (instead of the virgin material inflow). There are three commonly applied modelling approaches for this allocation issue (PE international 2014), these are:

1. **The recycled content approach**: All energy required for the end-of-life processes, is counted for the parent product system.
2. **The avoided burden approach:** All end-of-life processes are counted for the child product system. Hereby the end-of-life burden for the parent product is assumed to be zero. Importantly, this only yields for the recycled content. The material that is not recycled but disposed (waste incineration, landfilling), shall be accounted for the parent system.
3. **Value-corrected substitution:** Hereby, the end-of-life process burdens are deviated between the parent product system and the child product system. The related allocation factors be derived based on virgin-waste price ratio of the materials.

3.4 Comparison of the systems

In order to make the comparison between the two systems in a consistent and effective way, a similar method should be applied for both products. Importantly, assumptions should be made for both systems in a way that does not influence the outcome of the research (ISO 14067:2018 sd). For comparative LCA studies, extra requirements are set by the ISO (ISO 14067:2018 sd) for the goal and scope phase. Several relevant requirement are: an identical functional unit, system boundaries, similar performance.

According to the (ISO 14067:2018 sd), the following criteria shall be applied for the goal and scope phase:

- The product category definition and description are identical
- The functional unit is identical
- System boundary is equivalent
- Data description is equivalent
- Inclusion of in and outputs are equivalent.
- Data quality requirements (e.g. precision, completeness, representativeness), are the same
- Assumptions for the use and end-of-life stage are the same
- GHG emissions and removals are treated identical
- The units are identical

(ISO 14067:2018 sd)

In Table 9 an evaluation of this LCA on all these aspects is provided.

Requirement	Fulfilled	Description
Product category definition	Yes	Both 90 x 210, similar product segment (price, quality)
The functional unit	Yes	Functional unit is identical for both systems in this study
System boundary	Yes	Both include the full life cycle of each product
Description of data	Yes	The data is all obtained from the source databases, or collected from external parties but treated in a identical manner
Inclusion of in-, and outputs	Yes	For all aspects (transportation, material inflow, supply processes, the manufacturing and end-of-life phase), inclusion and exclusion of in and outputs are taken in a similar manner.
Data quality requirements	Yes	All parameters are evaluated in a similar manner, by use of the pedigree matrix or error estimations.
The use stage and end-of-life	Yes	For both systems, the full life cycle is considered. The use stage of both products is assumed to be neglecTable. However, the end-of-life stage of the evolve is a ground for discussion, as this phase can be counted for the Vivo product system or the recycled product system. Therefore, various scenarios are evaluated.
GHG emissions and removals	Yes	Regarding GHG emissions and removals, identical principles are applied for both mattresses. The same characterization factors are used to calculate the CO2 equivalents from other GHGs.
The units are identical	Yes	For both, the same units are used.

Table 9. Evaluation of this LCA, for the comperative LCA requirements from (ISO 14067:2018 sd)

3.5 Data quality

In the data collecting phase, the inventory analyses, the quality of the collected data is continuously evaluated by a three steps approach:

1. How certain is the collected inventory data point?
2. What is the relative importance or contribution to the output of the model?
3. Is there is a possibility for reducing relevant uncertainties, within practical reach?

A hierarchical decision tree is used to select the best data source for all gathered data, see Figure ... The collected factory data from factories, where collected by experts of the involved companies. Hereby, some voluntary guidelines for data are suggested. However, a protocol for data gathering from external facilities can enhance the consistency and effectiveness of this process and thus the data quality. This can be a ground for future research.

For the remainder, data from a generic source, as much as possible the Idematapp2020 inventory database is used. This database has a strong western European focus and assumes all materials to be delivered at the Port of Rotterdam. As a great majority of the production of Auping takes place in western Europe, this database is assumed to represent this LCA case well. However, with more or less 1500 rows, this database does not provide process data for all relevant processes. Therefore, important inputs and outputs may be missed in this LCA, which is a recognized problem for these researches (R frischknecht 2017). Eventually, most parameters are evaluated by a semi-qualitative approach, combining Pedigree and Monte Carlo. This is further explained in Section 4.9.

4. Life cycle inventory analysis: data collection

In this chapter the complete process of data collection in this study is discussed, in LCAs known as the life cycle inventory analysis. First, the different data sources types are categorized. Thereafter, the material inflow of both systems will be elaborated on, followed by the supply processes. Then, the quantities of the different material flows in the system are discussed. In some sections, inventory tables are provided, that describe relevant inventory data used in this LCA.

Questions answered in this section:

- What inventory data is used to model the different phases in the life-cycle?
- How can the material waste flows be approached?
- What energy resources mixes are assumed for the processes?
- What different end-of-life scenarios are relevant to evaluate?
- What uncertainties can be expected regarding to the collected data?

4.1 Data types

All **unit processes**, denoted as the smallest portion of a product system for which data is collected (ISO 14040:2006 sd), needs to be represented by at least one data point. The collected data is divided into two different categories: primary data and secondary data. In Figure 29, this data categorization is given. Hereby, primary data is defined as:

"Quantified value of a process or activity obtained from a direct measurement or a calculation based on direct measurements" (ISO 14067:2018 sd).

These can be direct measurements at the involved machinery, or an allocated portion of the total energy balance of a factory that can be dedicated to the chosen functional unit (in this case one mattress of 90x210).

Secondary data is defined as:

" Data that does not fulfil the requirement for primary data".

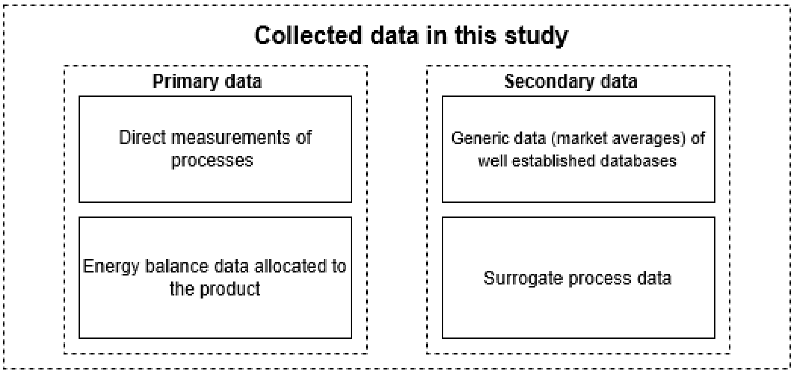


Figure 29. The definitions of primary data and secondary data for this LCA explained

Secondary data can be either generic (from standard databases) or taken from surrogate processes. Surrogate processes are production processes that are assumed to have a similar environmental impact, that can be process characteristics. It is plausible, that not all required site-specific data will be made available by external parties. Therefore, in practice the gathered LCA dataset includes a mixture of measured, calculated or estimated data, thus a mix of primary and secondary data. This is completely in line with the ISO (ISO 14067:2018 sd). However, for all data points still yields: these shall be representative for the processes they are collected for. (ISO 14067:2018 sd). To gather the data in this study in a consistent manner, the decision tree in Figure 30 is used.

ISO 14044 (2006a) defines data quality as "characteristics of data that relate to their ability to satisfy stated requirements". In other words, the quality of a LCA dataset depends on what users require from it. Since this LCA is a comparative study, it is especially important that assumptions for data gathering are made in a consistent manner for both systems. Therefore, a decision flowchart is used for data gathering in this LCI phase.

Primary data shall be used for those processes that are under operational or financial control of the company that is in lead of the LCA research. This is also the case for those unit processes that are most important and not under financial or operational control.

(ISO 14067:2018 sd)

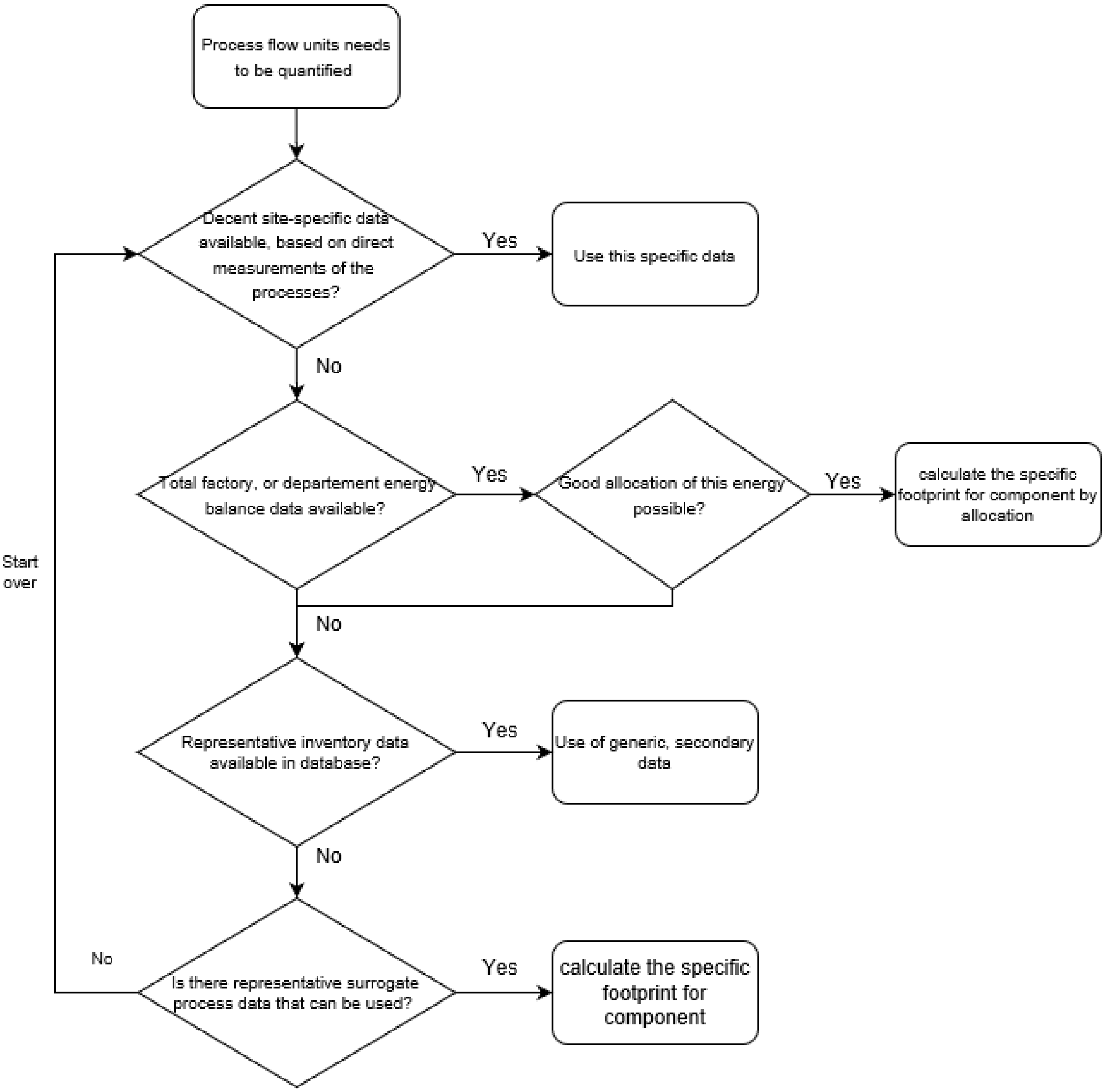


Figure 30. Decision chart used for process data collection (inventory data)

Table 10 lists for each mattress in this LCA the composition of the datasets. A carbon footprint study should use the best quality data available. Therefore, the used data is evaluated on quality, further explained in Section 4.9. For further research, this study may be improved by implementing a greater extent of primary data.

Phase	What	Data	Section in chapter
Supply	Material inflow	Secondary data	Section 4.2
	Suppliers	Primary and secondary data	Section 4.3
Manufacturer	Royal Auping	Primary data (with allocated energy)	Section 4.4
End-of-life	Recycling, waste incineration	Primary and secondary data	Section 4.6
Transportation data	Different transport flows in the system	Primary: delivery of new mattresses Secondary: all other transport	Chapter 5

Table 10. An overview of the dataset composition for each phase in this LCA

4.2 Material inflow in the systems

All components that are used for the mattresses, are made of a certain material or material mix. The inflow of materials, is considered to be the first step for both systems in this research. This inflow can consist of virgin material only, or can be a combination of virgin and recycled material. The carbon footprints of the materials that are used for each component, are all represented by secondary data from the (EcoinventV2.2) and the (Idematapp2020 sd) database.

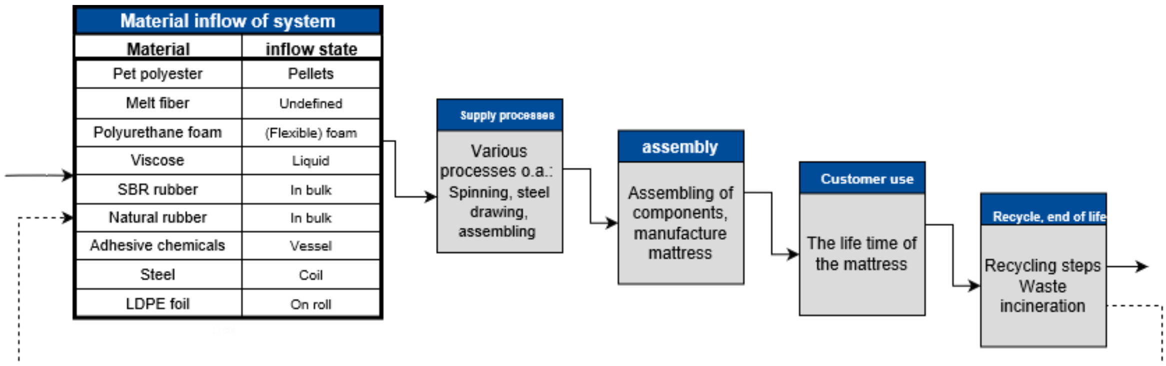


Figure 31. The material inflow is the first phase in the life cycles. The materials with assumed inflow state are provided left

The secondary data from the generic databases represent the carbon footprint for a material in a specific state. For example the data point *PET polymer pellet production* (Idematapp2020 sd), that represents the carbon footprint of PET in pellet form. The database considers an average process efficiency and energy mix for the area it is representative for. It does also include an estimation for the production infrastructure burden. Besides, the database assumes all former transportation steps, until the material arrives in the port of Rotterdam. In Figure 31, the box 'material inflow of system', lists all the different materials that occur in this study. Furthermore, it describes for each material the state it flows into the system i.e. "inflow state". Thereafter, the remaining processes that needs to be done to obtain the required component characteristics, e.g. knitting for a certain fabric, shall be added. This is described in the next section. In Table 11 and 12, the inventory data used for both mattresses is given for the material inflow phase. In Appendix 6, some specific assumptions for the collected data are explained.

Evolve | Material inflow							
Component	**Material inflow**	**Database**	**Amount**	**Unit**	**CO2e / kg**	**CO2e/ FU**	**Percentage**
Total amount	**Various**		**22,45**	kg/ FU		49,28	100%
Pocket spring pocket	PET polymer pellet	*Idematapp2020*	1,28	kg/ FU	2,12	2,71	6%
Pocket spring	50CrV4	*Idematapp2020*	8,64	kg/ FU	2,44	21,08	43%
DSM adhesive LA 1030	PET bottle grade	*Idematapp2020*	1,75	kg/ FU	2,19	3,83	8%
Mattress sides	PET polymer pellet	*Idematapp2020*	0,59	kg/ FU	2,12	1,25	3%
Ticking fabric wave white	PET polymer pellet	*Idematapp2020*	2,26	kg/ FU	2,12	4,79	10%
Border ticking fabric blue	PET polymer pellet	*Idematapp2020*	0,25	kg/ FU	2,12	0,53	1%
Top layer 3d mesh	PET polymer pellet	*Idematapp2020*	1,32	kg/ FU	2,12	2,80	6%
Comfort layer 3d mesh laminated	PET polymer pellet	*Idematapp2020*	2,89	kg/ FU	2,12	6,13	12%
Border filling	PET polymer pellet	*Idematapp2020*	0,46	kg/ FU	2,12	0,98	2%
Plastic packing mattress	film LDPE 50 mu	*Idematapp2020*	0,84	kg/ FU	2,07	1,741	4%
Support layer felt	PET polymer pellet	*Idematapp2020*	0,72	kg/ FU	2,12	1,53	3%
Felt bottom	PET bottle grade	*Idematapp2020*	1,45	kg/ FU	2,19	3,18	6%

Table 11. The inventory data for the material inflow of the Evolve

VIVO | Material inflow							
Component	**Material inflow**	**Database**	**Amount**	**Unit**	**CO2e / kg**	**CO2e/ FU**	**Percentage**
Total amount	**Various**		**22,45**	kg/ FU		67,72	100%
DPPS Pock.Med. 5Z.71,5x136x14 pocked	PP (Polypropylene)	*Idematapp2020*	1,28	kg/ FU	1,63	2,10	3%
DPPS Pock.Med. 5Z.71,5x136x14 spring	50CrV4	*Idematapp2020*	7,38	kg/ FU	2,44	18,03	27%
Pock.Schoulderz. 71,5x29x12,5 pocked	PP (Polypropylene)	*Idematapp2020*	0,20	kg/ FU	1,63	0,33	0%
Pock.Schoulderz. 71,5x29x12,5 spring	50CrV4	*Idematapp2020*	0,91	kg/ FU	2,44	2,22	3%
Ticking fabric	PET polymer pellet production	*Idematapp2020*	0,64	kg/ FU	2,12	1,35	2%
Ticking fabric	Viscose production	*Idematapp2020*	0,42	kg/ FU	1,50	0,64	1%
Border ticking fabric wash	PET polymer pellet production	*Idematapp2020*	0,28	kg/ FU	2,12	0,59	1%
Border ticking fabric wash	Viscose production	*Idematapp2020*	0,18	kg/ FU	1,50	0,28	0%
bath fabric U13 200 gr.	PET polymer pellet production	*Idematapp2020*	0,94	kg/ FU	2,12	1,99	3%
3D pressure divider schoulderzone	PET polymer pellet production	*Idematapp2020*	2,46	kg/ FU	2,12	5,21	8%
3D mesh 6.5 mm	PET polymer pellet production	*Idematapp2020*	1,53	kg/ FU	2,12	3,24	5%
Comfort layer PCM Latex	Natural rubber	*Idematapp2020*	2,08	kg/ FU	2,20	4,57	7%
Comfort layer PCM Latex	SBR (Styrene butadiene rubber)	*Idematapp2020*	2,08	kg/ FU	3,35	4,81	7%
Support Layer 87 x 197 x 1	PUR flex. block foam TDI	*Idematapp2020*	1,33	kg/ FU	2,91	3,87	6%
Visco shoulder zone	PUR flex. block foam TDI	*Idematapp2020*	0,86	kg/ FU	2,91	2,50	4%
Side layer PE	PUR flex. block foam TDI	*Idematapp2020*	2,03	kg/ FU	2,91	5,92	9%
HVE layer	PUR flex. block foam TDI	*Idematapp2020*	0,76	kg/ FU	2,91	2,20	3%
Head block	PUR flex. block foam TDI	*Idematapp2020*	0,72	kg/ FU	2,91	2,09	3%
Plastic packing mattress	film LDPE 50 mu	*Idematapp2020*	0,57	kg/ FU	2,07	1,18	2%
Sabamelt 4910 pillows	PF (resin)	*Idematapp2020*	0,40	kg/ FU	1,36	0,54	1%
Sabamelt 4910 pillows	Propylene	*Idematapp2020*	0,40	kg/ FU	1,35	0,54	1%
Aeroloft PB	PET polymer pellet production	*Idematapp2020*	0,63	kg/ FU	2,12	1,34	2%
Felt bottom	PET bottle grade	*Idematapp2020*	1,00	kg/ FU	2,19	2,19	3%

Table 12. The inventory data for the material inflow of the Vivo

4.3 Supply processes in the system

Thereafter, the inflow materials are processed through one or more production processes so that they fulfil the purchase requirements as agreed upon with the manufacturer. Figure 32 shows this phase in the life cycle. In Table 13 and 14, all processes analysed in this thesis are given (displayed on the next two pages). Not for all suppliers, the exact processes are known. In that case, an estimate of an expert is used to estimate the processes. In Appendix 7, a selection of the assumptions regarding the supply data gathering is given.

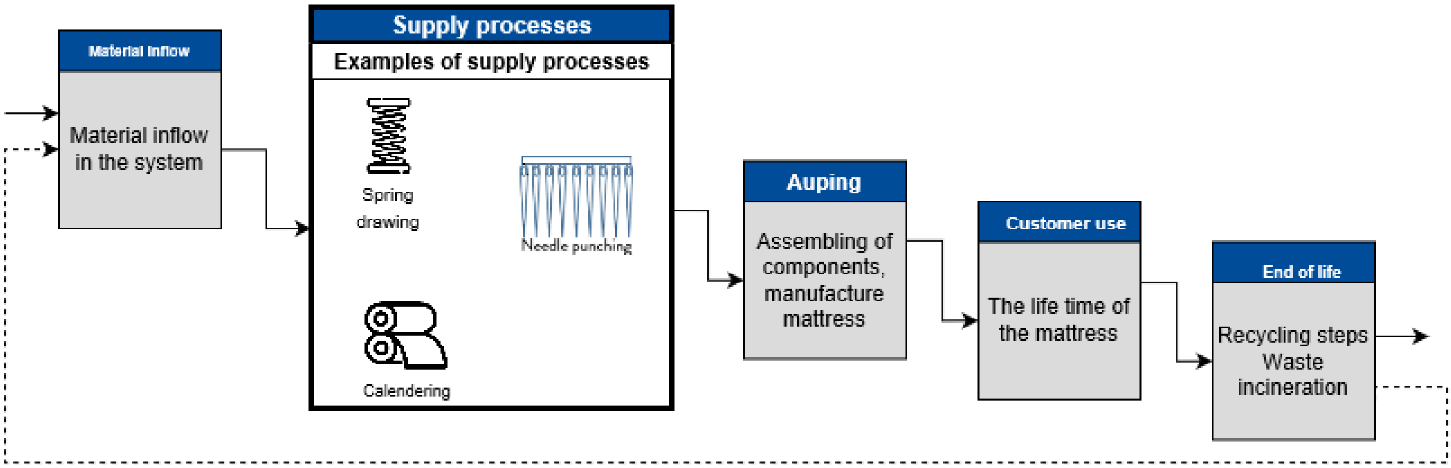


Figure 32. Second phase in the life cycle concerns the supply processes

In this research, the majority of these processes are textile processes, such as spinning, knitting and thermoforming. The non-textile components are obtained by different processes, like mixing or wire drawing. In general, the largest energy share is required for the material transformation process (the production process), and less to the facility infrastructure and transportation burdens. Especially for chemical processes, relevant for the adhesives, this is the case:

Environmental burden of the infrastructure directly needed for the production of chemicals, are considerably small compared to the processing of these materials. (H. Althaus 2007).

Most processes are non-chemical in this LCA, so the impact of background processes may contribute more. However, for practical reasons, in this first LCA the focus is set on the main processes and less specific attention is given on the facilities and indirect processes. A more comprehensive study, with a licensed database and sophisticated application may give more accurate results. For various components, site specific information for the related processes could be collected for this study. For the remainder, the type of production steps are estimated by various textile experts and thereafter represented by secondary data. For both mattresses this sequence of processes is simplified, whereby the production steps that are assumed to have the main impact (in terms of carbon footprint), are included. In the following sections, important assumptions for these processes are discussed.

Evolve | Supply processes						
Component	**Material inflow**	**Data type**	**Weight**	**kg CO2e / kg**	**CO2e/ FU**	**Percentage**
Total amount	**Various**			**total CO2e:**	**18,83**	**100,0%**
Pocket spring Pocket	Spinning process	Secondary	1,28	0,73	0,93	**5,0%**
Pocket spring Pocket	Calendaring, rigid sheets/RER S	Secondary	1,28	0,38	0,48	**2,6%**
Pocket spring 16cm Endless	Deep drawing steel	Secondary	8,64	0,42	3,62	**19,2%**
DSM adhesive LA 1030	Glue mixing process	Secondary (surrogate)	1,75	0,33	0,58	**3,1%**
Mattress sides	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,59	0,73	0,43	**2,3%**
Mattress sides	Felt needling	Secondary	0,63	0,05	0,03	**0,2%**
Mattress sides	Calendaring, rigid sheets/RER S	Secondary	0,59	0,38	0,22	**1,2%**
Ticking fabric wave white	Spinning extruder polymer filaments (80-500 dtex)	Secondary	2,26	0,73	1,65	**8,8%**
Ticking fabric wave white	Spinning extruder polymer filaments (80-500 dtex)	Primary	2,26	0,73	1,65	**8,8%**
Ticking fabric wave white	knitting (info by Innofa)	Primary	2,26	0,10	0,22	**1,2%**
Ticking fabric wave white	Washing and Drying (info by Innofa)	Primary	2,26	0,09	0,21	**1,1%**
Border ticking fabric blue	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,25	0,73	0,18	**1,0%**
Border ticking fabric blue	Spinning extruder polymer filaments (80-500 dtex)	Primary	0,25	0,73	0,18	**1,0%**
Border ticking fabric blue	knitting (info by Innofa)	Primary	0,25	0,06	0,01	**0,1%**
Border ticking fabric blue	Washing and Drying	Primary	0,25	0,18	0,04	**0,2%**
Top layer 3d mesh	Spinning extruder polymer filaments (80-500 dtex)	Secondary	1,32	0,73	0,96	**5,1%**
Top layer 3d mesh	knitting 300 dtex	Secondary	1,32	0,06	0,08	**0,4%**
Top layer 3d mesh	heat setting and washing synthetic fabrics	Secondary	1,32	0,74	0,97	**5,2%**
Comfort layer 3d mesh laminated	Spinning extruder polymer filaments (80-500 dtex)	Secondary	2,89	0,73	2,10	**11,2%**
Comfort layer 3d mesh laminated	knitting 300 dtex	Secondary	2,89	0,06	0,17	**0,9%**
Comfort layer 3d mesh laminated	heat setting and washing synthetic fabrics	Secondary	2,89	0,74	2,13	**11,3%**
Border filling	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,46	0,73	0,33	**1,8%**
Border filling	Felt needling	Secondary	0,46	0,05	0,02	**0,1%**
Border filling	Calendering, rigid sheets/RER S	Secondary	0,46	0,38	0,17	**0,9%**
Plastic packing mattress	***Amount of CO2e dedicated to supply processes***	-	-	-	0,49	**2,6%**
Support layer felt	Spinning extruder polymer filaments (80-500 dtex)	Primary	0,72	0,73	0,53	**2,8%**
Support layer felt	Feltneedling	Primary	0,72	0,05	0,04	**0,2%**
Support layer felt	Calendering, rigid sheets/RER S	Primary	0,72	0,38	0,27	**1,5%**
Felt bottom	Felt needling (by VEBE) Primary	Primary	1,45	0,05	0,07	**0,4%**
Felt bottom	Thermofixation (gas) Primary	Primary	1,45	0,02	0,03	**0,1%**
Felt bottom	Thermofixation (electiricty) Primary	Primary	1,45	0,02	0,03	**0,1%**

Table 13. Inventory data for the supply processes of Evolve. Only the data that is used for the results in Chapter 6 is given here

Vivo | Supply processes						
Component	**Material inflow**	**Data type**	**Weight (kg)**	**Kg CO2e / kg**	**Kg CO2e/ FU**	**Percentage**
Total amount	*Various*			***total CO2e:***	**19,35**	**100,0%**
DPPS Pock. pocked	Spinning extruder polymer filaments (80-500 dtex)	Secondary	1,28	0,73	0,94	**4.8%**
DPPS Pock.Med. pocked	Calendering, rigid sheets/RER S	Secondary	1,28	0,38	0,48	**2.5%**
DPPS Pock.Med. spring	Deep drawing steel	Secondary	7,38	0,42	3,09	**16.0%**
Pock.Schoulderz. pocked	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,20	0,73	0,15	**0.8%**
Pock.Schoulderz. pocked	Calendering, rigid sheets/RER S	Secondary	0,20	0,38	0,08	**0.4%**
Pock.Schoulderz. spring	Deep drawing steel	Secondary	0,91	0,42	0,38	**2.0%**
Ticking fabric	knitting (info by innofa)	Primary	1,06	0,10	0,10	**0.5%**
Ticking fabric	Washing and Drying	Primary	1,06	0,09	0,10	**0.5%**
Ticking fabric	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,64	0,73	0,46	**2.4%**
Ticking fabric	Spinning viscose fibres (80-500 dtex)	Secondary	0,42	0,18	0,08	**0.4%**
Border ticking fabric wash	knitting (info by innofa)	Primary	0,46	0,34	0,16	**0.8%**
Border ticking fabric wash	Washing and Drying	Primary	0,46	0,40	0,19	**1.0%**
Border ticking fabric wash	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,28	0,73	0,20	**1.0%**
Border ticking fabric wash	Spinning viscose fibres (80-500 dtex)	Secondary	0,18	0,18	0,03	**0.2%**
bath fabric U13 200 gr.	knitting (info by innofa)	primary	0,94	0,16	0,15	**0.8%**
bath fabric U13 200 gr.	Washing and Drying	primary	0,94	0,07	0,07	**0.3%**
bath fabric U13 200 gr.	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,94	0,73	0,68	**3.5%**
3D pressure divider schoulderzone	Spinning extruder polymer filaments (80-500 dtex)	Secondary	2,46	0,73	1,79	**9.3%**
3D pressure divider schoulderzone	knitting 300 dtex	Secondary	2,46	0,06	0,14	**0.7%**
3D pressure divider schoulderzone	heat setting and washing synthetic fabrics	Secondary	2,46	0,74	1,82	**9.4%**
3D mesh 6.5 mm	Spinning extruder polymer filaments (80-500 dtex)	Secondary	1,53	0,73	1,12	**5.8%**
3D mesh 6.5 mm	knitting 300 dtex	Secondary	1,53	0,06	0,09	**0.5%**
3D mesh 6.5 mm	heat setting and washing synthetic fabrics	Secondary	1,53	0,74	1,13	**5.8%**
Comfort layer PCM Latex	***Amount of CO2e dedicated to supply processes***				3,31	**17.1%**
Support Layer 87 x 197 x 1	Cutting foam	Secondary	1,33	0,10	0,13	**0.7%**
Visco shoulder zone	Cutting foam	Secondary	0,86	0,10	0,09	**0.4%**
Side layer PE	Cutting foam	Secondary	2,03	0,10	0,20	**1.1%**
HVE layer	Cutting foam	Secondary	0,76	0,10	0,08	**0.4%**
Head block	Cutting foam	Secondary	0,72	0,05	0,04	**0.2%**
Plastic packing mattress	***Amount of CO2E dedicated to supply processes***	-			0,49	**2.5%**
Sabamelt 4910 pillows	Glue mixing process	Secondary	0,40	0,13	0,05	**0.3%**
Aeroloft PB	Spinning extruder polymer filaments (80-500 dtex)	Secondary	0,63	0,73	0,46	**2.4%**
Aeroloft PB	Feltneedling	Secondary	0,63	0,05	0,03	**0.2%**
Aeroloft PB	Calendering, rigid sheets/RER S	Secondary	0,63	0,38	0,24	**1.2%**
Felt bottom	Felt needling (by VEBE) Primary	Primary	1,00	0,05	0,05	**0.3%**
Felt bottom	Thermofixation (gas) Primary	Primary	1,00	0,02	0,02	**0.1%**
Felt bottom	Thermofixation (electiricty) Primary	Primary	1,00	0,02	0,02	**0.1%**
Felt bottom	Spinning extruder polymer filaments (80-500 dtex)	Secondary	1,00	0,73	0,73	**3.8%**

Table 14. Inventory data for the supply processes of Vivo. Only the data that is used for the results in Chapter 6 is given here

4.4 Auping factory processes

In this section, the energy required for the assembling of a mattress at Auping is explained. First the production facility of Auping is briefly discussed. Then, the allocation of the yearly total energy consumption, to the production of one mattress is explained. Then, the method to derive the energy consumption for the different mattresses sizes in this study, is explained. Lastly, the energy burden for the different mattress types, such as Vivo and Evolve, is evaluated.

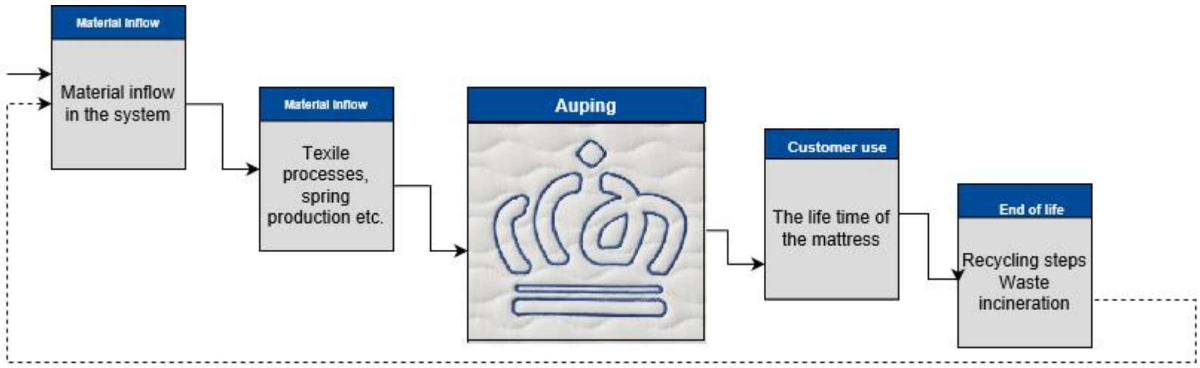


Figure 33. Third phase in the life cycle, the assembling at Auping

4.4.1 Production facility

Auping produces all its products from one centralized production facility in Deventer. This production facility is deviated into three different factories, that all harvest different production processes, that are:

1. The textile factory
2. The wood factory
3. Steel factory

The mattress production process that takes place at Auping, is schematically represented in Appendix 2. The textile factory is the only relevant factory for the mattresses, since the full manufacturing process takes place here. In this process several half-fabricates are produced in parallel, and assembled subsequently. For the production processes of mattresses, solely electrical energy is being consumed. This electricity is a mix of certified green energy and energy from solar panels on the factory rooftop. The only process within the factory that uses fossil fuels, is the powder coating process, which is not required for mattresses production. The temperature of the factory is regulated by a ground-coupled heat exchanger, located beneath the factory grounds. This installation uses only a very limited amount of electrical energy to facilitate the heat exchange.

4.4.2 Electricity groups

The production of mattresses only takes place in the textile factory. The resource consumption is not being monitored for all machinery separately. Instead, the electricity grid is divided into groups. Each of the groups is connected to a part of the machinery, that all are connected to the same electricity point. By the use of sensors, Auping tracks the electricity consumption for these groups separately.

The following groups are relevant to evaluate in this LCA, as all mattress production steps take place here:

- Naaizaal (sewing room)
- Auping hart (Central area Auping factory)
- Matras box
- TD/service verlichting (Maintenance and facility services)
- Compressor (1until 4)

To define the electricity consumption for the production per FU (one mattress), this energy shall be allocated. The principle of allocation factors is explained in Section 3.3. These allocation factors are group specific, since mattresses require more processing in some groups and less in others. One example:

In the Naaizaal (sewing room) the energy consumed is mainly related to mattress production, as most processes of the mattress production process take place here. At the group "mattress box", more processing of other products takes place. Therefore, a lower portion of the resource used, should be allocated to mattresses.

To approach this energy consumption per mattress for each group, a maintenance and site expert of Auping is consulted. Consequently, the allocation factors in Table 15, are obtained. These are used to calculate the yearly energy dedicated to mattress production, for each of these electricity groups. These values are somewhat rough estimates of the energy share between mattresses and the other product groups, based on the number and type of energy intensive steps for the products. The total energy and water consumption per year for each of these groups is listed as well. One example for the allocation of the "Naaizaal":

In the Naaizaal (sewing room), besides mattresses other textile products are produced. However, these products are simple in comparison to mattresses; often only 2 energy requiring steps are needed against over 10 for mattresses. Therefore, 80 percent of the sewing room energy is allocated to mattresses. Which is an conservative guess (higher bound for energy consumption).

Group	Dedicated to mattresses	Dedicated other products	Average total resource consumption 2017-2019	Allocated energy share for mattresses
Naaizaal	0,8	0,2	436.760 MJ	393.084 MJ
Matras box	0,5	0,5	323.059 MJ	161.530 MJ
Auping hart	0,5	0,5	193.944 MJ	96.972 MJ
TD/Service verlichting	0,3	0,7	70.608 MJ	21.182 MJ
Compressed air (compressor)	0.2	0,8	659.703 MJ	131.940 MJ
Fresh water	0.3	0,7	3453 m3	1.036 m3

Table 15. Allocation factors and energy shares for mattress production

4.4.3 Energy use per size

The energy consumption per mattress is also related to the size; a mattress that is 1.40 wide requires more energy than an exemplar of 0.90. In this LCA, the functional unit concerns a mattress that is 2.10 x 0.90 meter (L x W). Since there are many different sizes produced in the factory, an factor is required to derive the energy for the specific mattresses in this study. It is unlikely that the energy level is completely proportional to the size, as the start-up energy of the machine and background process, will be more or less identical for small and large size mattresses. Arbitrarily, the mattresses that have a width in the range (0,70 – 1,00) is given a size factor 1, the remainder (1.20 – 2.00) is given a factor 1.75. Thus, the production of mattresses that are twice the size, are assumed to have an energy burden that is more or less 75 percent larger. This number is deviated in the uncertainty analysis, to see the effect of different factors. The lengths of the mattresses only vary to a small extent (1.90 – 2.10 m), thus are assumed to affect the production energy not significantly. In Table 16, the discussed size factors are given.

Width	0.70	0.80	0.90	1.00	1.20	1.40	1.60	1.80	2.00
Sales per size 2019	1%	13%	51%	7%	2%	5%	5%	13%	3%
Size factor	1				1,75				

Table 16. The percentage sold mattresses per size and the assigned size factors

4.4.4 The energy burden per mattress

To approach the energy required to produce one mattress in the Auping factory, Formula 2 is used. To obtain the energy usage for one mattress, the energy use of each group shall be divided by the total number of mattresses, corrected for the different sizes. For the number of mattresses yearly produced, the sales data from 2017 to 2019 is taken. This number is more or less equal to the yearly production, since only produces made-to-order. Only a correction for the estimated rejected production is made.

$$E_m = \frac{\sum_{g=1}^{6} (E_g \, A_g)}{(n_s \, s_s + n_l s_l)\,(1+r_j)} \qquad (2)$$

Where

E_m = Energy required to produce one mattress of (90 x 210) (w x l) at Auping

E_g = The total amount of resources used by group g

A_g = Factor to allocate the total energy dedicated to mattress production for each group g

n_s = The number of small mattresses (0,70 – 1,00) sold a year

n_l = The number of large mattresses (1,20 – 2,00) sold a year

s_s = The size factor for small mattresses

s_l = The size factor for large mattresses

r_j = The assumed percentage rejected production

4.4.5 Energy consumption of different mattress types

All conventional Auping mattresses, such as Cresto, Vivo and Maestro, follow a very similar process flow within Auping. Presumably, the internal production process of these different models yield a roughly similar carbon footprint, for the same mattress sizes. The Evolve mattress is not yet included in the energy data of recent years, as this product line is released first in 2020. Consequently, various scenarios are evaluated for the manufacturing process at Auping for the Evolve. In the first scenario, the Evolve is assumed to have an equal energy consumption at Auping as the Vivo. The second scenario assumes a more modern logistic system for the assembling of parts, by use of robots. For this second scenario, the energy requirement of this system is seen as additional energy burden. In Table 17, an overview of the inventory data for the manufacturing at Auping can be found for both mattresses.

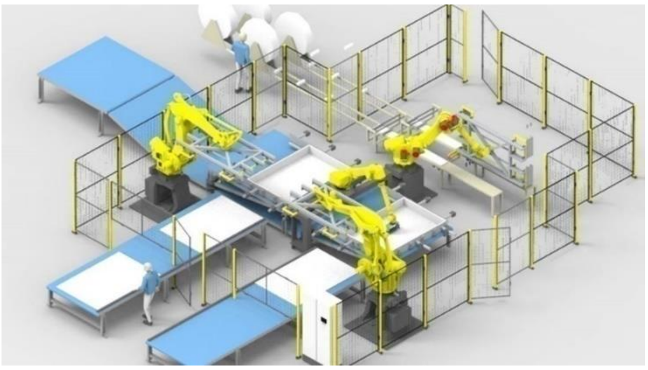


Figure 34. Concept of the robotic assembly system for Evolve

Auping factory - Evolve and Vivo					
Electricity group	**Kg CO2e e/ MJ**	**Kg CO2e e/ m3**	**Energy per F.U (MJ)**	**Volume (m3)**	**CO2e/ FU**
Total amount Vivo and Evolve (scenario 1)					**0,92**
Total amount Evolve (scenario 2)					**1,26**
Electricity groups					
Naaizaal (kW-hr)			5.3		0,45
Matras box (kW-hr)			2.2		0,18
Auping hart (kW-hr)			1.3		0,11
TD/Service verlichting (kW-hr)			0.3		0,02
Electricity use due to compressed air					
Compressor 1-4			1,8		0,15
Other resources					
Fresh water use				0,014	
Estimate for additional Robots Evolve					
3 robots (1,5 kWh each, **15 min**)			4.1		0,34
Carbon footprint for resources at factory					
Electricity mix	0,084				
drinking water Europe		0,001			

Table 17. The inventory data of the assembly processes at Auping. The energy is assumed to be equal for both mattresses, except the robotic system, that gives an additional burden

4.5 The use phase

The use phase of the mattress is assumed to yield a neglectable small contribution to the carbon footprint, only caused by the rinsing of the ticking. Each mattress type is available with ticking that can either be rinsed by dry-cleaning, or in a washing machine. The emissions related to the use-phase, are assumed to be small for both mattresses. A recent study indicates that one wash cycle yields on average 0.5 kg CO2e, for European countries (Shahmohammadi et al., 2018). However, consumers generally do not rinse the ticking frequently over its lifespan (Auping 2020). Besides, from a emission perspective, no significant differences are expected between both mattresses for this phase. Therefore, in this LCA, the carbon footprint of the use phase is not taken into account for the mattresses[8]. However, the use and cleaning of the ticking may impact other environmental aspects as well such as marine life, or human health. This may be a ground for further research.

[8] This phase is assumed to contribute less than 5% to the total carbon footprint and is therefore cut-off.

4.6 End-of-life processes

The phase that differs most for both mattresses, is the end-of-life phase. In this section, the end-of-life phase for both mattresses is explained and quantified. First, the assumed parameters for the end-of-life of Vivo are discussed. Then, the end of life of Evolve is given, that is represented mainly by test data.

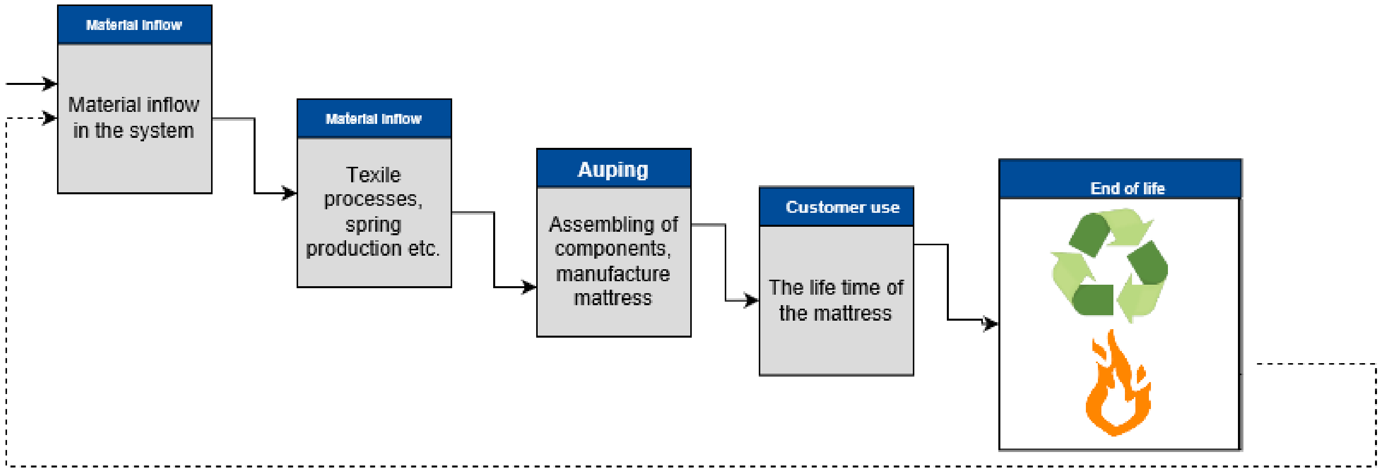


Figure 35. The last phase in the lifecycle, the end-of-life. In this phase recycling or waste processing takes place

4.6.1 End-of-life Vivo

4.6.1.1 the end-of-life path

The conventional path of mattresses, including the Vivo, is shown in Figure 36. As already mentioned in Section 3.2.3, the vivo follows an open loop recycling process. Hereby, mattress recyclers ask a certain gate-fee for disposed mattresses. This value, is roughly 5€/ mattress in the Netherlands (ABN AMRO 2019). The price for waste processing is higher, and can reach up to 12€ per mattress (ABN AMRO 2019). The remainder is assumed to follow the regular end-of-life path for mixed materials in The Netherlands: waste incineration with energy recovery. According to a report of the Utrecht Sustainability Institute (Driel 2018), around 38% of the mattresses are recycled in the Netherlands. Furthermore, for one of the large mattress recyclers in the Netherlands, more or less 6%[9] of these collected mattresses cannot be recycled and are incinerated (Narinx 2016). These numbers are used in this LCA. However, the capacity of Mattress downcycler has been extended over the recent years, with a new factory opened in 2020 (+200.000 mattresses yearly). The recycled share may have been increased over the recent years, but is still not approaching a 100 percent. As this value is likely to affect the total carbon footprint significantly, the effect of higher and lower rates are evaluated in the scenario analysis. In Figure 36, the simplified end-of-life of the conventional mattresses is given with the assumed values, in this thesis represented by the Vivo mattress.

Assumed numbers	
Collected for recycling	38 %
Not accepted for recycling; incinerated	6%
***Overall :* Recycling rate**	36%

Table 18. Key numbers for Vivo end-of-life

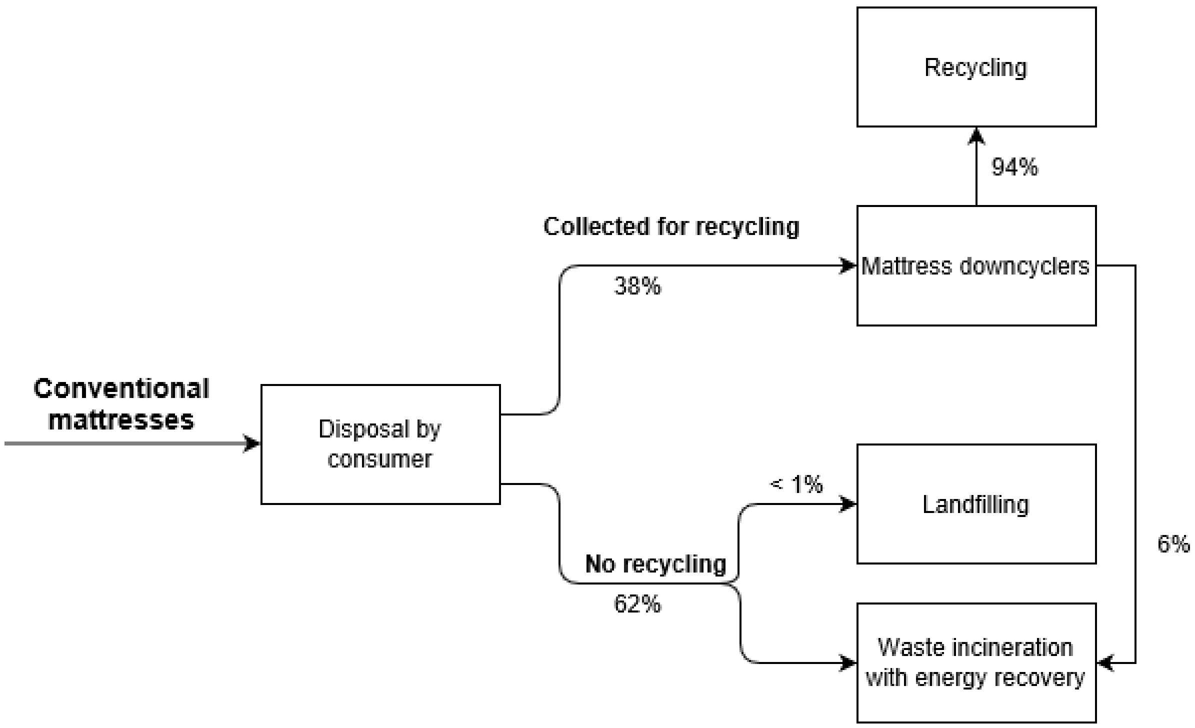


Figure 36. Schematic overview of the end-of-life path of Vivo mattresses, with the assumed numbers

[9] A flow diagram for one of the large mattress recyclers in the Netherlands, is given in Appendix 1.

4.6.1.2 Scenario's Vivo – end-of-life processes

As already mentioned in Section 3.3, there is an on-going debate on how to deal with the allocation for open loop recycling (Vogtländer 2015). In this LCA the following scenarios are evaluated:

1. No recycling at all, all mattresses are incinerated. No steel recycling credits are given.
2. All end-of-life processes are counted for the mattress life cycle.
   End-of-life recycling processes = mattress
3. All end-of-life processes are accounted for the secondary system
   End-of-life recycling processes = e.g. insulation foam.
4. A part is allocated to both systems, based on a specific material characteristic
   E.g: End-of-life processes (0.7 : 0.3) for mattress : downgraded products.

The part that is incinerated (66%), is never part of the "child" life cycle. Only the part that is recycled is part of the debate.

The first scenario is used to see the carbon footprint, if no recycled would been executed. In this case, all polyester is incinerated. The difference between this scenario and a recycling scenario gives an impression of the potential benefit of recycling.

The second scenario assumes the recycling process being part of the end-of-life system of the Vivo. The total carbon footprint is taken until the recycled material leaves the factory.

The third scenario assumes that all end-of-life processes count as first step of the life cycle of the secondary product (e.g. the insulation foam, or secondary textile fibres). In this scenario, the life cycle of the Vivo stops when the waste materials are collected and sorted.

In the fourth scenario, allocation is based on specific material properties of the material before recycling and after recycling. The selected characteristic should reflect the quality ratio between this materials well. Hereby, ISO (ISO 14067:2018 sd) suggest the following hierarchical order, if feasible:

1. *Physical properties*: Allocation is based on a physical characteristics such as the mass properties.
2. *Economic value*: Allocation is based on the market value ratio of the material before and after recycling.
3. *Number of uses*: Allocation is based on the number of life cycles of the material. A waste paper example of this system can be found in literature (C. Hohental 2019). This is a proper option for material that is recycled various times, while remaining the same function.

The first hierarchical option, is assumed to be infeasible for this recycling case. There is no unique material property that relates to quality, for the different material applications. For example:

"The density of a polyester textile fabric might have some relationship to quality: more dense, is more expensive. The same does not apply for insulation foam: very dense means less insulation capabilities". Thus, density is no gauge for quality of both applications of the plastic material"

Furthermore, the third option, is not applicable as the material yield another function in its secondary life span and is only being recycled once. The second option, economic value allocation, would be the only feasible allocation alternative for this LCA. However, the mattress recyclers ask a "gate-fee", a charge for disposal, for the collection of old mattresses. This gate-fee is required to have a feasible business proposition (ABN AMRO 2019), as the secondary material has no or very little value. As stated in ISO (ISO 14067:2018 sd):

"In the case of A = 0, i.e. complete down-cycling, no recycling credit is given".

Therefore, only scenario 1 and 2 are further analysed. In Table 19 some key inventory data for the Vivo end-of-life is given.

4.6.1.3 Delayed pulse

An alternative method to allocate the end-of-life burden of open loop recycling systems, relates to the extended life time of materials. Hereby, a discounting factor for the extended life of the material is given to primary product, for the delay of combustion. For this method, a discounting factor of 1% per useful extended year is suggested in a handbook for LCAs, (ILCD 2010). However, this method is subject to heavy debate for years (Vogtländer 2015), as it is often quite uncertain how long the secondary material life will last. Therefore, there is refrained from this concept in this LCA.

End-of-life | Vivo					
Process	**Reference**	**CO2e / kg**	**CO2e/ FU[10]**	**Material efficiency (% output)**	**Notes**
Polymers recycling					
Plastic waste, Collection and sorting		0.09	0.55		This is always assumed to be part of Vivo
Recycling mixed polymer		0.34	1.47		This is for the scenario recycling energy = mattress.
Steel recycling	Steel, recycling credit closed loop (56% virgin part in market mix)	-0.99	-8.59	-	From Idemat2020
Other waste flows					
Waste incineration	Flexible Polymer Foam, waste incineration with electricity	1.79	5.65		From Idemat2020. Recycling waste assuming 36% effectively recycled
	Natural rubber waste incineration with electricity	-1.76	-2.03		
	SBR (Styrene butadiene rubber) waste incineration with electricity	1.66	1.92		
	PP (Polypropylene) waste incineration with electricity	1.42	1.35	-	
	(Polyethylene terephthalate) waste incineration with electricity	1,35	5,37	-	
	PE (Polyethylene) waste incineration with electricity	1,34	0,71		From Idemat2020 Disposed at the customer

Table 19. Inventory table of the end-of-life for the Vivo

[10] Considering that 36% of the mattresses is effectively downcycled, remainder incinerated

4.6.2 End-of-life Evolve

4.6.2.1 Current state of development

After the useful life of the Evolve mattresses, these will be collected by Auping. All end-of-life processes that follow, are still in an early development phase. Presumably, the following processes will be required to obtain new raw material for yarn production:

- Disassembling
- Shredding
- Extruding
- Granulating.

Furthermore, agglomeration and polycondensation may be required depending on the chosen recycling strategy. Figure 37 is a schematic representation of this recycling process. In Section 2.3.2 these processes are briefly explained. The goal of these recycling steps is to obtain granulate that meets the specifications of the yarn supplier, such that new fabric of virgin quality can be made. Hereby, a critical value is the "Intrinsic viscosity"; an indication for the quality preservation of polymers. An estimation of the energy consumption and process efficiency for all tests are listed in Table 20. As there is no data on closed-loop mattress recycling available yet, the primer tests results will be used in the LCA model. Hereby, for each of the processes, the most representative test data is selected to approach the total recycling energy. In future research this inventory data can updated.

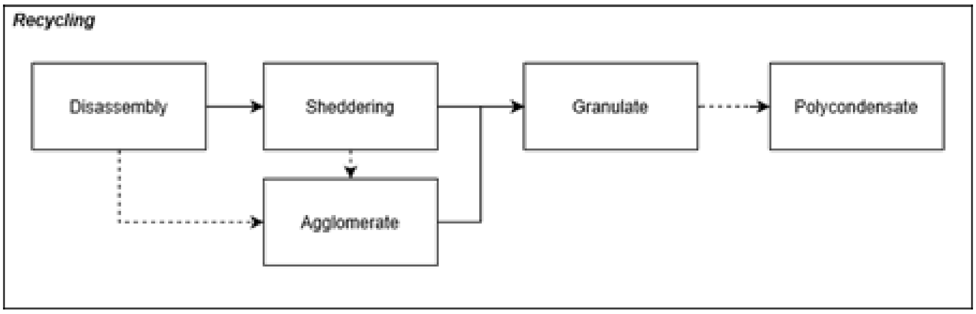


Figure 37. Schematic representation of the end-of-life processes of Evolve

4.6.2.2 Disassembly tests

The thermoplastic adhesive in the Evolve mattress melts at a relative low temperature, around 130 degrees. By heating the mattress around this level, the different components can be separated again. By this, the pocket springs and all polyester layers can be separated, without affecting PET material and steel springs (with higher melting points). For the PET layers it is not clear yet, which can be recycling effectively together. However, more insights are expected soon, as intensive testing will continue.

4.6.2.3 Small scale test

The first disassembly tests were done at a small scale: a slice of the mattress (circa 5 percent, excluding ticking) was heated in a consumer convection oven. 15 minutes were required at 180 degrees Celsius to disassembly this part successfully. For this test, the estimated energy for one complete mattress is assumed to be proportional to the size, thus more or less 20 times that for the small part. This is most likely an overestimation for the energy consumption, as for the small part a relatively large amount of empty space was heated as well. The average power consumption of the oven is estimated based on a home appliance research of (Issi, and Kaplan 2018), that assumed similar test circumstances (convection, temperature, small size).

4.6.2.4 Conveyor oven test

The first tests with a complete mattress are done in a conveyor convection oven. After unzipping the ticking, the complete core of the mattress was put in the machine. Then, the mattress was slowly transported by the conveyor through the heating device. After an estimated 3-4 minutes, the mattress could be disassembled successfully. Sometimes, various parts were still attached. For these cases, the mattress was heated again in the oven, mostly 1-2 minutes. For this LCA, a conservative estimate of 5 minutes is taken. The oven regulates its heat by a thermostat, that turns the oven either on full power (50 kWh), or in idle mode (3 kWh) depending on the measured temperature. For this LCA, the average power consumption is estimated based on the time ratio "full power - idle power" during one of the tests. However, this disassembly method is not yet optimized and the energy consumption can likely be improved in the future.

Overall, the disassembly test results are not sufficient robust and should be interpreted only as first indication for the energy consumption.

4.6.2.5 Recycling tests

After the disassembly of the mattress, the components can be re-cycled or re-used. The steel springs are brought by a steel recycler or may be re-used The latter requires further research, and will only be done in full transparency (Auping 2020). The polyester layers will be recycled to new polyester granulate by mechanical or chemical recycling. For now, all layers are assumed to be treated by mechanical recycling, which is currently being tested. In the next sections these tests are explained and the assumed numbers used in this LCA are given in Table 20 'End-of-Life Evolve'.

4.6.2.6 Lab scale recycling tests

The first recycling tests were done at a lab scale at Senbis, a recycling laboratory in The Northern part of The Netherlands. Hereby a batch of 300 kg P.I waste, has been agglomerated and extruded. No shredding took place in this test, as the material could be directly agglomerated. From this first batch, an output of 261 kg granulate is obtained (87%). This material did not meet the required viscosity in the specifications yet, thus is a polycondensation step followed. Hereby, an amount of 66 kg granulate was polycondensated for 16 hours. Consequently, a batch of 64 kg of recycled granulate is acquired (97%), that meet the specified intrinsic viscosity of the yarn producer. Based on the information provided by Senbis, an estimate of the agglomerate and extruding process is made. The power consumption of the tumble dryer for polycondensation is unknown. Therefore, the average power consumption for an industrial tumble dryer is taken instead as LCI input. According to this company, the material efficiency would be significantly higher for larger volumes. The losses for extruding are indicated are indicated at 200 kg, for 5000 kg inflow material. This would give a recycling rate of 96% for agglomeration and extraction together.

4.6.2.7 Real scale test

The first tests with more representative amounts of granulate (1000 kg), were done at the company Starlinger in Austria. Hereby a fully integrated machine is used for the processes shredding, extruding and granulating. Hereby, the textile material is transported by conveyor belt into the machine and is processed into granulate, collected at the end of the machine. At date of this thesis, the test results of this process are not yet available. However, to obtain the right quality it is likely that a polycondensation step is required. Alternatively, the material can be mixed with virgin material, to obtain a material flow that meets the specifications. For this complete process, the first tests indicated a power consumption of 0.35 kWh/ kg obtained material. The material losses are estimated at 4% by the recycling company.

4.6.2.8 Scenario used for the LCA "Mechanical recycling"

From these tests, the estimated energy consumption for the complete end-of-life process is defined. This value is used for the mechanical recycling scenario in the LCA model. The following tests are included in this scenario:

- **Disassembly by the conveyor oven tests.** This is a upper bound for the disassembly energy as the process is likely to be improved over time.
- **The recycling process at Starlinger**. This recycling machine is more likely to be used for recycling by Auping in the future, in comparison with the smaller scale Senbis exemplar.
- **Polycondensation**. The granulate from the recycling process at Starlinger is presumably not of good enough quality for the spinning of yarn. Therefore, polycondensation is a likely next step for the granulate. The Senbis polycondensation process is taken, as this is the only test done.
- **Steel.** Is assumed to be brought to a steel collected point in the Netherlands. Where it can be recycled (mixed with other scrap wastes).
- **Waste incineration for the polyester waste.** The percentage lost material in the recycling process (1- recycling rate), is assumed to follow a regular waste process; waste incineration with energy recovery. This is as well the case for the plastic PE packaging used for customer delivery.

The recycling rate is determined by the two tests that have been done. The potential efficiencies, that are indicated to be higher, are not taken into account. Consequently, the recycling rate is calculated as follows:

- Lab scale test:
  - Agglomeration + extruding (87%)
  - Polycondensation (97%)
- Real scale test:
  - Shredding + extruding (96%)
- <u>Average</u>
  - Average of processes with "1" (91.5%)
  - Polycondensation (97%)

  average : (89%)

Therefore, for the scenarios of mechanical recycling in this thesis, the recycling rate is assumed to be 89%. This can be seen as a rather conservative value, since the material efficiency of the lab scale test is indicated to be higher for larger amounts.

4.6.2.9 Recycling efficiency for chemical recycling

However, instead of mechanical recycling, various parts of the mattress may also be treated by chemical recycling. Chemical recycling is still in an early development stage and not applied on an industrial scale. As a result, there is not a lot information available on the material and energy efficiency for this process. From the Idematapp2020 database, the use of so called "upcycling credits" for plastics can be used as rough indication for the efficiency of chemical recycling (J. Vögtlander 2020). Due to the uncertainty of this data, the results for this scenario are provided in Appendix 10.

End-of-life | Evolve							
Process	**Reference**	**Amount inflow material**	**Energy consumption (MJ/ kg)**	**CO2e / kg**	**CO2e/ FU**	**Material efficiency (% output)**	**Notes**
Polymers recycling							
Disassembly	Small oven test	0,01 m3 in test 3% (excl ticking)			1.95	100%	Test small slice of mattress in small home appliance convection oven
	Conveyor oven test	0.43 m3 in test 100% (exl ticking)			0.79	100%	Full mattress test in conveyor convention oven
Lab scale tests recycling	Agglomeration	300 kg in test	0.48	0.072	0.74	87%	
	Extruding + Granulating		0.4	0.06	0.62		
Large scale tests	Shredderring + extruding + granulating	1000 kg in test	1.26	0.17	1,63	96%	
Polycondensation	Polycondensation	66 kg in test		0.14	1.36	97%	24 hours test
Other waste flows							
Waste incineration	Waste incineration with electricity (recycling waste)	0,30 kg per mattress		1.35	0.92	-	From Idematapp2020. Recycling waste assuming 93 % recycling efficiency.
	Waste incineration PE packaging	0,80 kg per mattress		1.34	1.12	-	From Idematapp2020 Disposed at the customer
Steel recycling	Steel, recycling credit closed loop (56% virgin part in market mix)	8,6 kg		-0.99	-8.59	-	From Idematapp2020
Recycling scenario							
Recycling scenario	Conveyor oven test		0.79	0.39	0.79	100%	
	Shredderring + extruding + granulating		0.35	0.17	1.63	96%	
	Polycondensation			0.14	1.36	97%	
	Waste incineration (recycling waste)			1.35	0.92		
	Waste incineration PE packaging			1.34	1.12		
	Total recycling process energy				**6.91**		
	Spared on waste incineration				-19.43		
	Spared on virgin material energy				-12.41		
	Steel, recycling credit closed loop			-0.99	-8.59		
	Total end-of-life				**-33.52**		

Table 21. Inventory data for the end-of-life phase of Evolve. Below, the main recycling scenario for Evolve is given for this LCA

4.7 Energy resource production process

All processes included in this study, require a certain energy resource. This energy supply can be divided into two categories: direct resources and indirect resources (or direct energy and indirect energy).

- *Direct resources:* are those consumed close to the specific process, such as the use of heat energy by a gas driven oven, or the use of electrical energy by a sewing machine. In this thesis four forms of direct energy are relevant, these are: Electricity, gas, diesel and compressed air.
- *Indirect resources:* are used for the production of the direct energy carrier in direct form; thus the resource of the direct resource. In this LCA, Electricity is the main form of direct energy that is often generated far away, far from the location where it is used. This electricity can be generated by use of fossil, nuclear, or more sustainable resources (wind, solar, geo, bio weight). In practice, the origin of the used electricity is often a mix these, whereby the 'mix composition', is strongly geographically dependent. According to the Idemat 2020 database, the standard energy mix in the Netherlands is 0.15 kg CO2 equivalents per kg material. Therefore, in this LCA this value is taken for all companies, unless the actual energy mix is explicitly known. This is a rather conservative assumption, as more suppliers will probably use green energy sources. All data points withdrawn from the generic databases, already assume a certain electricity mix (based on the representative area and field of process).

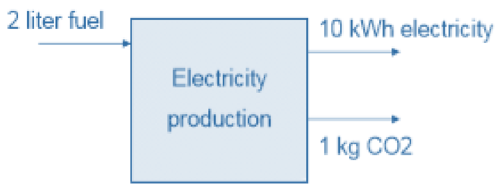


Figure 38. Direct resource electricity, indirect resource: fuel

Figure 38 is an example for electricity production. The fuel can be seen as indirect and the electricity as direct resource. Table 21 lists the assumed energy mixes for the different suppliers. If only secondary data is used for a supplier, the energy mix is not defined. In the most right column, the related carbon footprint per MJ is listed.

Energy mix required?		Heat energy	E. indust. NL	E. Indust. West EU	E. Indust. General	Dutch wind energy	Solar panel	**energy mix (kg CO2e / MJ)**
<u>Suppliers</u>								
Royal Auping	yes	0%		58%			42%	0.08
Agro Int. GMBH & Co. KG	no							
DSM / Niaga	yes		100%					0.15
Enkev	no							
Jilana a.s.	no							
Innofa BV (knitting)	yes		100%					0.15
Libeltex NV/ TWE	yes							
Radium Foam BV [2922]	no							
Recticel B.V 2525	no							
RVC industriële verpakking	no							
Saba dinxperlo Exp BV	yes	75%	12,5%				12,5%	
VEBE	yes		100%					
Latexco	yes	50%	25%				25%	0.06
Italfeltro	no							0.15
<u>Recycling</u>								
In Netherlands	yes		100%					0.15
in western Europe	yes			100%				0.13

Table 22. The assumed energy mixes for suppliers and recycling locations. If no mix is known, the region standard is assumed (conservative guess)

4.8 Wastes: Material flow quantities in the system

4.8.1 Material flow modelling in the system

In each process in the supply chain, material wastes occur. These losses can have various origins: cutting waste, waste outflow of fluids, catalysator uses, or rejected products. For the material losses in this this study, Formula 3 is used to estimate the resulting material flow amounts for each process in the supply chain[11].

$$x_{t-1} = (x_t * (1 + w_t)) * (1 + r_t) \quad (3)$$

Where:

$$x_1 = \text{The amount of material used for process t}$$

$$w_t = \text{The percentage of material waste (Scrap, by product) occurring at process t}$$

$$r_t = \text{Percentage rejected products at process t}$$

Indices:

$$t = \text{Production process (e.g spinning, knitting, cutting to propper size)}$$

This formula can be explained as follows: If a process causes a loss of material, w_t , then the process prior to this, x_{t-1}, requires an additional output of that waste amount. The same principle applies for the rejected production. By rejected production (r_t), all products that do not meet the quality requirements and are disposed, are meant. What numbers are used for these parameters in this LCA, is explained in Appendix 11.

[11] For practical reasons, some processes are aggregated, whereby all processes in that cluster are assumed to use the same material flow.

4.9 Uncertainty in LCAs

4.9.1 Relevance of uncertainty evaluations

LCA is supposed to be a supportive tool, for quantitative decision making (M Raynolds and M. D. Checkel 1999), for organizations, governments and scientists. For the involved decision makers that use the study results, a relevant question is:

"In what certainty range the outcomes of a LCA can be expected"?

Due to the use of generic data, numerous assumptions and the limited data support from stakeholders, the confidence of LCA results can become limited (Nicole Bamber 2020). In practice modelling decisions and assumptions sometimes lead to deviating study outcomes for identical cases. (Oskar Larsson Ivanov 2019). Therefore, thorough evaluation and quantification of uncertainties can strengthen the reliability and effectiveness of life cycle analyses.

The definition "uncertainties" can be explained as the phenomenon that measured or estimated values do not coincide with the true values, but deviate in a probabilistic manner. In LCAs a great number of parameters and variables (in case of scenarios), are often required to calculate the desired impact indicators. Uncertainties in LCAs occur at many different stages and can be categorized as follows (Lloyd and Ries 2007):

- ***Parameter uncertainty:*** Also called data uncertainty, can be related to the sample data (size, variability) or measurement reliability. The uncertainty of each of the inventory data points in the LCA, such as carbon footprint per kg material, distances and recycling efficiencies, can be addressed as parameter uncertainty.
- ***Scenario uncertainty:*** Uncertainties based on normative choices such as: functional unit, geographical scale and methodological decision making, e.g. the allocation of energy between various products systems.
- ***Model uncertainty:*** Uncertainties as a result of limitations of mathematical models, thus simplifications of the reality. This includes linear modelling of non-linear processes and the calculations of characterization factors. The assumed factors to express the effect for various GHGs in CO2e equivalents in Table 5, are determined by simplified models too.

There is a remarkable discrepancy between LCAs relative uncertain outcomes (a uncertainty range of 20% is no exception), and the assessment of the data quality. A research of (Bamber et al., 2020) indicated that in no more than 20 % of the evaluated (n=2687) LCA studies since 2014, uncertainty analyses of any kind were conducted. Especially in comparative studies, whereby impacts of two or more products are compared, uncertainty evaluation may be critical for justified decision making (Bamber et al., 2020).

4.9.2 Uncertainty in this LCA

This LCA compares the impact of two different mattresses, that differ especially in material composition and the end-of-life phase. Especially for comparative LCAs, uncertainty needs to be considered to avoid wrong conclusion drawing. However, the required statistical data in LCAs is often not or limited available. This problem was already recognized in the late 90s (Raynolds et al., 1999):

"In most cases adequate samples of data are not available to generate a specific probability distribution function, so some pre-defined mathematical function must be used".

In this LCA, most data is single parameter data, which yields that no statistical data is available or only one sample is known from measurements. For cases with insufficient LCA data available, the 'Pedigree Matrix' can be used to evaluate and indicate the data quality. This technique is explained in the next section. Importantly, all uncertainty estimations that are not based on statistical data, should be interpreted as very rough indications.

4.9.2.1 Pedigree

If statistical uncertainty data for parameters are not available, it can still be relevant to have an uncertainty indication for both the individual parameters and overall system outcomes. A Pedigree approach can be used to quantify these uncertainties in a semi-quantitative manner (Greenhouse Gas Protocol sd). Hereby, parameters are evaluated by a set of Data Quality Indicators, DQIs. These can be defined as follows:

"Quantitative or qualitative terms for defining data characteristics that serve as benchmarks against which data quality can be assessed to determine whether data quality goals have been met" (Bakst 1995)

In this LCA, the following are evaluated (Weidema and Wesnaes 1997):

- **Reliability**:
  Relates to the data sources and data acquisition method, used to gather the data (T Bicalho 2017). This score is independent of the research goal and only indicates the data quality in general. Therefore, this score is identical regardless the study it is used.
- **Completeness**:
  Relates to the statistical properties of the data. Is the used value determined by sufficient number of data points? This score is independent of the research goal as well.
- **Temporal representativeness**:
  Indicates the time correlation between the used data and the chosen LCA time span.
- **Geographical representativeness:**
  Indicates how well the data represents the chosen geographical area of the LCA. One example: *If the row IDEMATAPP2020 Bio-Cotton China would be used to model bio-cotton of European origin, a low score is given.*
- **Technological representativeness:**
  Accessing other technological correlations, such as process or material fit. One example: If the steel in the product is no exact match with the listed steels in the inventory database, a lower score is given.

Each of the evaluated parameters receive a score (i.e., very good, good, fair, poor), based on expert reviewing. The scores are given through a list of predefined criteria. The scoring criteria for this LCA, are given in Appendix 12. By use of a conversion matrix, the given qualitative scores are translated into values between 1.00 and 2.00. The used conversion factors in this LCA can be found in Table 22.

However, not all criteria are applicable for the used secondary data. Reliability and completeness and refer to the quality of the statistical data, which is not known for data from databases in this study. However, it is assumed that the Idematapp database is carefully maintained by the University of Delft, therefore all Idemat data is given a "good" score for these categories in this LCA. In Appendix 13 all scores are listed for the evaluated parameters.

Score	Reliability	Completeness	Temporal representativeness	Geographical representativeness	Technological representativeness
Very good	1,00	1,00	1,00	1,00	1,00
Good	1,10	1,05	1,10	1,02	1,20
Fair	1,20	1,10	1,20	1,05	1,50
Poor	1,50	1,20	1,50	1,10	2,00

Table 23. Conversion factors used in this LCA, as proposed by the (GHG Protocol)

One additional uncertainty factor is obtained in an alternative manner: the basic uncertainty. This data is preferably defined by statistical information, such as sampling data. However, when this information is not available, predefined values can be used based on the process' category (Muller et al., 2014). The latter is done in this LCA. Hereby, the values suggested by the (Greenhouse Gas Protocol sd) report are used. These values can be found in Table 23.

Category	Basic uncertainty value
Themal energy	1,05
electicity	1,05
semi-finished products	1,05
raw materials	1,05
transport services	2
waste treatment services	1,05
infrastructure	3
CO2E emmisions	1,05
Methane emmissions from combustion	1,5
Methane emissions from agriculture	1,2
N2O emissions from combustion	1,5
N2O emissions from agriculture	1,4

Table 24. Suggested basic uncertainty factors (GHG protocol

If scores are given for all categories of a parameter, Formula 4 can be used to obtain one total uncertainty factor (Greenhouse Gas Protocol sd). This total uncertainty is defined as square of the geometric standard deviation, GSD^{2}. A confidence interval describes with what certainty (in this case 95%), the mean can be expected within that range. Subsequently, the obtained parameter uncertainties can be used as input for statistical tools such as Taylor Series expansion, or Monte Carlo simulation. In this LCA the latter is used to evaluate the total system uncertainty.

$$\sigma_g^2 = e^{\sqrt{\ln^2 U_b + \sum_{i=1}^{5} \ln^2 U_i}} \quad (4)$$

Where

$$U_b = \text{basic uncertainty factor}$$

$$U_1 = \text{Uncertainty factor for reliability}$$

$$U_2 = \text{Uncertainty factor for Completeness}$$

$$U_3 = \text{Uncertainty factor for Temporal representativeness}$$

$$U_4 = \text{Uncertainty factor for Geographic representativeness}$$

$$U_5 = \text{Uncertainty factor for other Technological representativeness}$$

4.9.2.2 Monte Carlo simulation

The Monte Carlo simulation, named after the famous casinos in the Mediterranean city, is a technique that allows the modelling of complex systems, without deep knowledge of the underlaying technical mechanism. By use of a Monte Carlo simulation, life cycle models can be tested for variation in the input, random sampling over a chosen distribution. Consequently, the simulation allows decisions makers to see the effect of uncertainty of inventory data on the environmental impact of the total system (Parsons 2016). For Monte Carlo simulation, the following aspects should be set:

- A probability distribution (Section 4.9.2.3)
- The distribution specific parameters (Section 4.9.2.4)
- A number generated at random
- The number of runs (Section 4.9.2.5)

4.9.2.3 Distribution choice

To perform a Monte Carlo simulation, a distribution is needed to model the uncertainties of the parameters. The probability distribution of a random variable, is a mathematical function that describes the occurrence of outcomes of the observed system (Qin and Suh 2017). This distribution can be used to inform decision makers of certain statistics, such as the 95% confidence interval, the standard deviation or the mean. In a Monte Carlo simulation, this distribution is used to simulate variability in observed parameters.

Ideally, for all individual parameters, the most suitable distribution is chosen based on real statistical data. If sufficient data is available, a goodness of fit test can be done, to see how well a situation can be modelled by the evaluated distribution. However, by the lack of statistical data, a more generalized method is frequently used in LCAs: one or a few distributions are selected, that is used to represent all parameters. What distribution fits this general application over all LCI data best, is a source of discussion in literature (Raynolds et al., 1999), (Muller et al., 2014), (Qin and Suh 2017). Two frequently applied distributions are the normal distribution and the lognormal distribution. Both distributions have some advantages. For the normal distribution, two advantages are:

- Many statistical parameters are proven to be modelled well by this distribution (Singh 1998).
- The distribution has a symmetric shape, which makes it a convenient choice for many statistical models. E.g. a confidence interval can easily be derived.

The lognormal distribution has one important advantage for modelling physical parameters in LCAs:

- An analysis over all data of the Ecoinvent database (Qin and Suh 2017), concluded the lognormal distribution as most suitable to model the uncertainty for that LCI data.
- It is strictly positive, random sampling for a lognormal distribution will not return negative numbers (Muller et al., 2014). In the Monte Carlo simulation this will be a great benefit. Negative numbers will result in impossible scenarios. For example:
  "A parameter value of -0.20 for PET production, means a reduction of amount of CO2e for this production"

Monte Carlo simulations have been tested for both distributions. However, for practical reasons, the normal distribution is selected to model the uncertainties in this LCA. In future research, the uncertainty analysis can be enhanced by selecting the most suitable distribution per parameter.

4.9.2.4 Parameters normal distribution

The probability density function of a normal distribution can be described by Formula 5.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2} \quad (5)$$

Where

x = *normal random variable*

σ = *standard deviation*

μ = *mean*

To generate a random value[12], the mean and standard deviation should be specified. The mean is given (the parameter value), and the standard deviation is derived by applying the Pedigree approach. According to the pedigree approach, the squared geometric standard deviation is given by equation .. In order to use this measure, a transformation is required, this done through the following steps:

First the coefficient of variation is calculated by the relation (Muller, 2014) given by Formula 6.

$$CV = \sqrt{e^{\ln^2 \sigma_g} - 1} \quad (6)$$

Then from the CV, the standard deviation σ for the normal distribution could be derived by formula 7.

$$\sigma = CV * \mu \quad (7)$$

As μ is given by the inventory parameters, CV can be calculated. Combining these formulas, a model is made in excel, which is linked to all inventory data in the life cycle model. By deviating all parameters in every run, the uncertainties of the life cycle carbon footprints are approached. Sufficient runs are required to obtain a good indication of the total system uncertainties. In the next section, the derivation of this number of runs is given.

[12] To generate a random variable X, the build-in excel function *´Rand()'* is used. This random number generator gives a value between 0 and 1 each time the sheet is calculated.

4.9.2.5 Number of runs per experiment

In Monte Carlo Simulations, for every experiment a predefined number of runs are performed. In each run a random number is drawn for each parameter. If too many runs are utilized per experiment, the computational effort can become problematic. On the other hand, if insufficient runs are performed, the simulated uncertainty can become unreliable (heijungs 2020). To find a convenient number of runs for each model (Evolve, Vivo), five experiments have been utilized for 10, 100, 1000 and 5000 runs. Hereby, the average carbon footprint of all runs each experiment is determined. As shown in Figure 39, for 1000 runs of the Evolve, the means of the experiments are within a relatively small range, that is <0,3% of the absolute value. The same test is done the Vivo, which led to identical conclusions. For this number of runs, disproportional influences of outliers on the results, seems to be smoothened. Therefore, 1000 runs are performed for every experiment in this LCA.

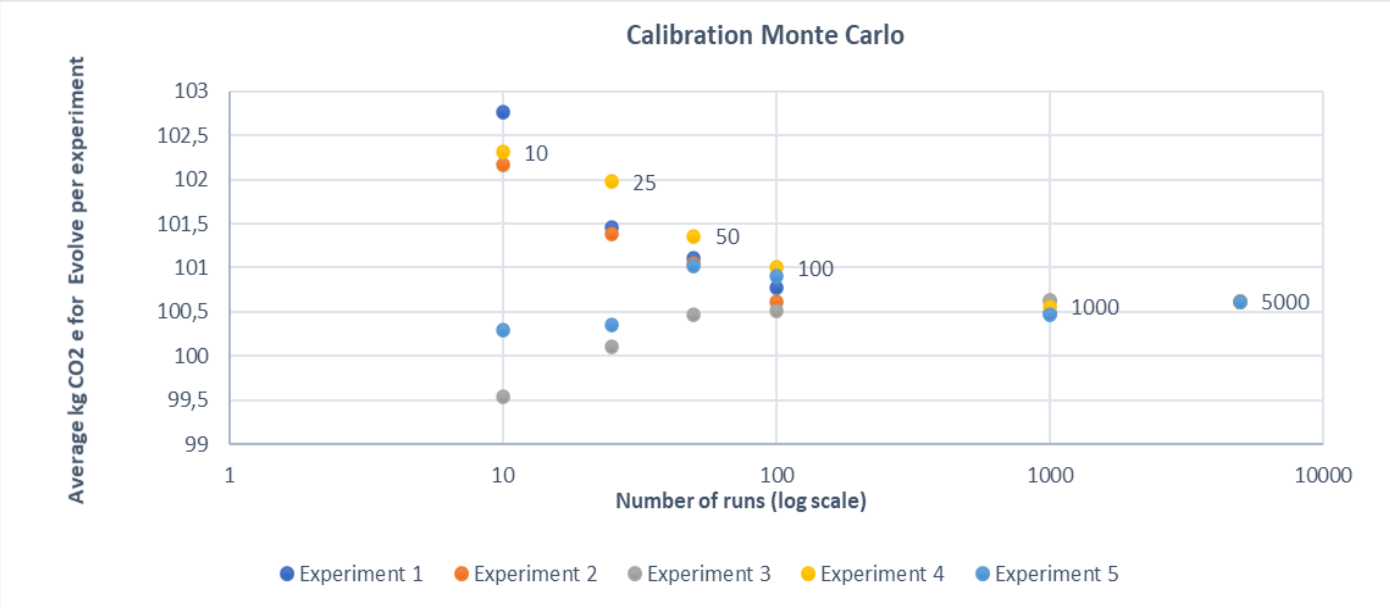


Figure 39. Five experiments per run size are done, from 1000 runs, the mean value of the Evolve system stabilized more or less

4.9.2.6 Reporting parameter uncertainty

There are various ways to present the obtained parameter uncertainty. First, the probability density functions for both mattresses can be plotted in one graph. In Figure 40, this is done for the carbon footprints of both mattresses. On the horizontal axis, intervals (bins) are made for the total carbon footprint. On the vertical axis, the number of runs within a certain interval are given. Comparative study results that are visualized in this manner, can be interpreted as follows:

- **Almost no overlap between the graphs:** One of the products performs significantly better
- **Great overlap between both graphs**: No firm judgements should be made.

For the specific case in Figure 40, the conclusion can be drawn that the Vivo performs with great certainty worse, as it has a higher carbon footprint for mostly all runs.

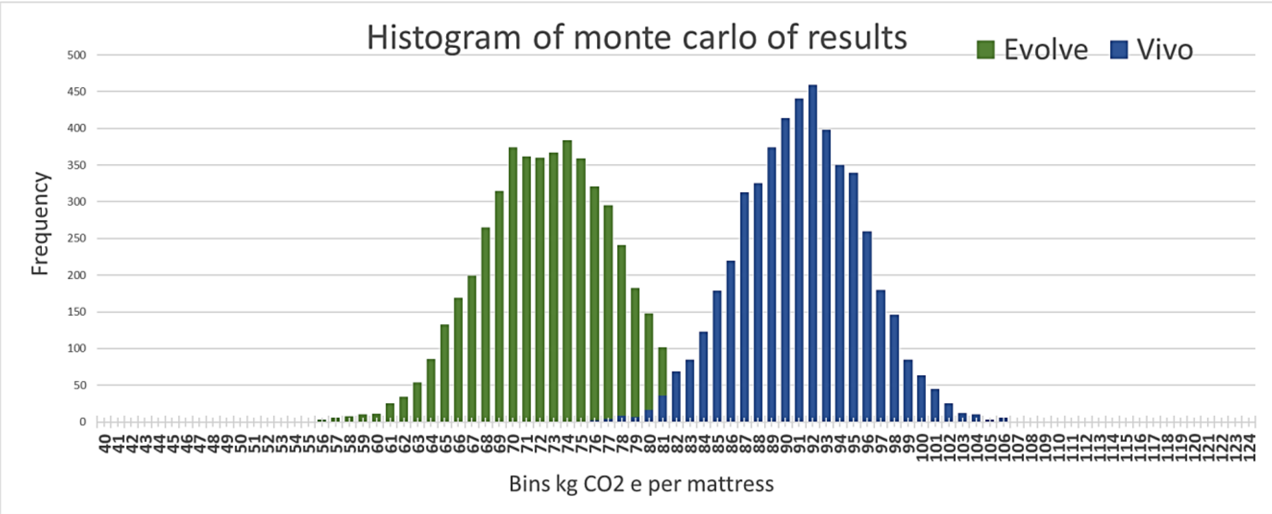


Figure 40. The monte carlo results for 1000 runs per system. There is limited ovelap between both

Second, the simulated results can be used to define a confidence interval for the mean carbon footprint of the systems. The 95% interval for the mean of a normal distribution can be determined by formula 8.

$$[C_l, C_u] = [\hat{x} - z * \sigma, \hat{x} + z * \sigma] \quad (8)$$

Where:

C_l = *lower limit of confidence interval*

C_u = *upper limit of confidence interval*

$\hat{x}$ = *mean of the normal distribution*

z = *The standard score. For 95% interval this is 1.96*

σ = *standard deviation of the normal distribution*

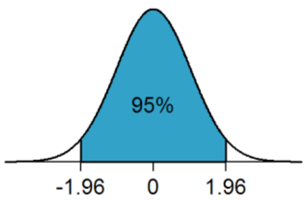


Figure 41.
95% confidence interval of normal distribution

Figure 41 represents this confidence interval for a normal distribution, that can be explained as follows:

"With 95% certainty, the mean of the results can be expected between the upper and lower bound"

For this LCA, this interval indicates the uncertainty range, which can be interpreted as:

"The carbon footprint of the system (the mean), can be expected with great certainty between these limits".

Thus, this interval can be presented additionally to the results, to give an impression of the uncertainty. Therefore, for the most important results in this LCA, this uncertainty is indicated by the error bars. An example is given in Figure 42.

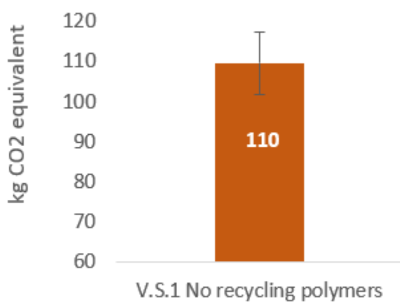
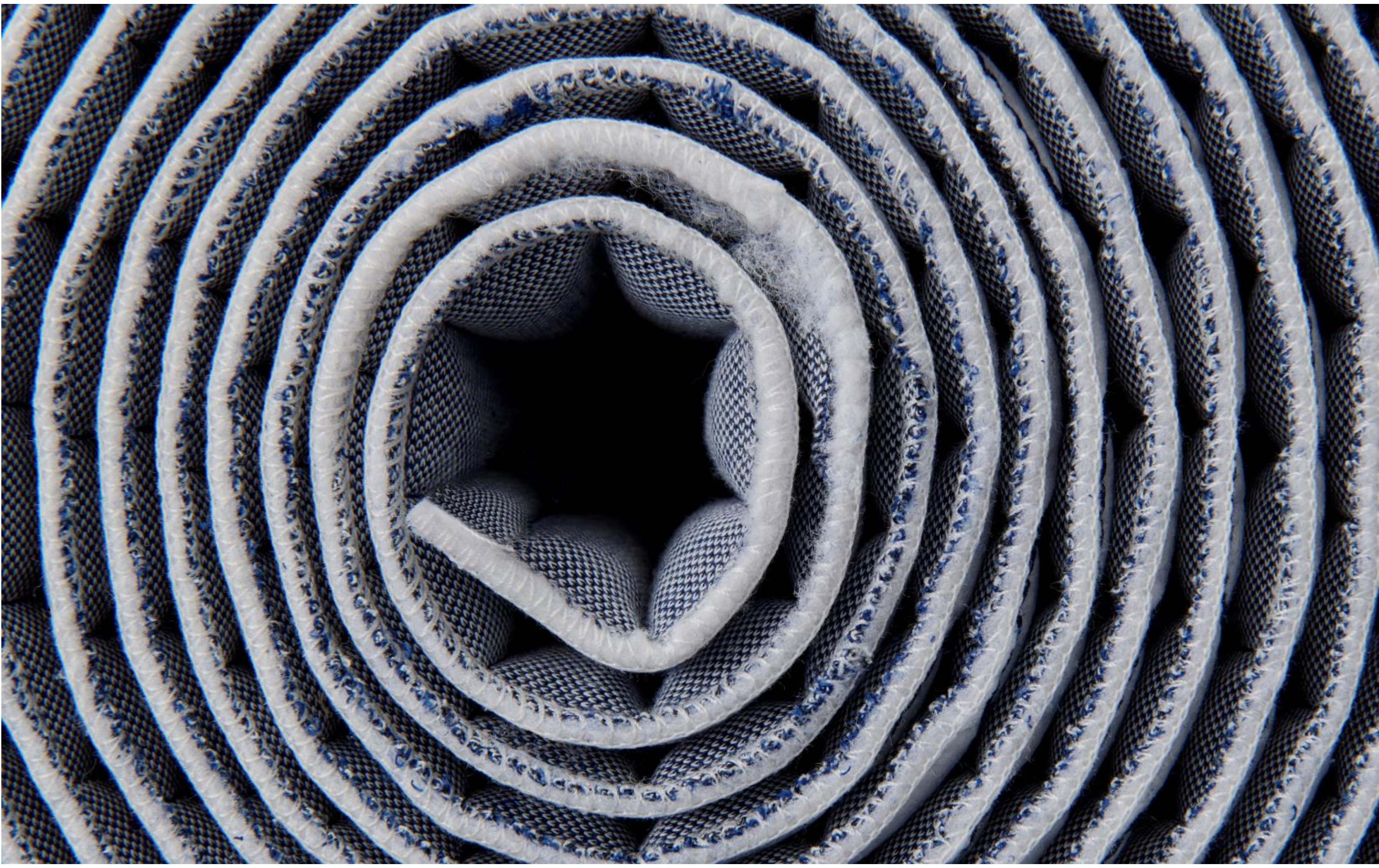


Figure 42. The error bar gives an indication of the 95% confidence interval for the mean

5 Transportation

In this chapter, first the role of transportation in LCAs in general is discussed. Then, a brief explanation of the different transport flows in the life cycles is given. Thereafter, the use of generic data for transportation modelling in LCAs is discussed. Then, the different parameters used to define the carbon footprints for each flow are explained. Lastly, the carbon footprint for all transport legs in the system is provided visually.



The following questions are answered here:

- What aspects of transportation affect the carbon footprint?
- How does the transport network of both life-cycles look like?
- How can the average transport distances be estimated?
- What impact can be expected for each transport flow?
- What are relevant transport scenarios to evaluate?

5.1 Relevance of transport in LCAs

In the life cycle of products, raw materials, semi-finished goods, components and products are transported. Transport can be a dominating factor in LCAs (Vogtländer 2015). A comparative study of LCAs in the 90s, indicated that 5-15 percent of the environmental burden of the LCAs under study, can be dedicated to transportation (Jorgensen et al.,1996). Although transportation vehicles increased in combustion efficiency and improved on various environmental other aspects over the years; transportation still seems to be a relevant issue in LCAs. A great part of the transportation in the mattress life-cycle concerns road transport, utilized by trucks. According to a report of (Transport & Environment 2016), trucks represent only 3% of the road vehicles. However, they account for 25% of EU overall transport emissions, likely to growth even further to 40% in 2030. In the life cycle of the mattresses, a great number of trucks are involved. Besides, as various logistical supply chain decisions for the Evolve mattress are still to be made, the analysis of various transportation scenarios may help. For this reason, special attention is given to transportation in this LCA.

5.2 Transportation in both systems

In this section, the transportation flows in the life cycles of both mattresses are discussed. Hereby, materials are transported in various forms. In Table 23, the different forms are listed. The related transport flows are briefly explained in the next sections.

Material forms
Raw materials
Semi-finished components
Components
Mattresses
Old mattresses
Recycled materials
Recycling waste

Table 23. Material forms

5.2.1 Transport of raw materials

Both systems start with an inflow of virgin raw materials. For the Vivo mattress, this flow of virgin material is significantly larger, as there is no use of recycled content for the production of the new mattresses. In other words, all required material for new components is virgin here. For the circular mattress Evolve, all post-use materials shall be transported to the recycling factory and from the recycling factory back to the initial suppliers. In Figure 43, this situation is drawn schematically.

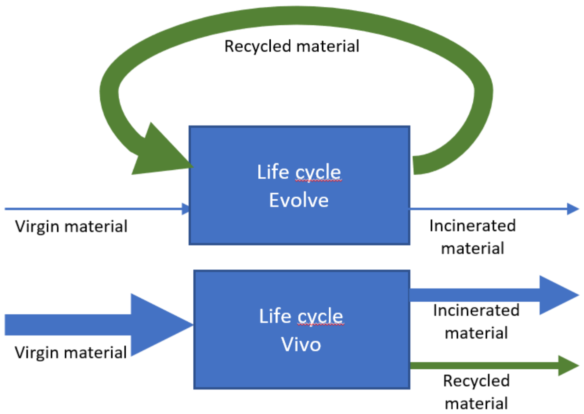


Figure 43. Vivo has a relatively large virgin material flow, compared to the Evolve. The width of the arrows give an impression of the size of the material flows

Most material data from standard databases, already include the transportation burden to some extent. For the used data from Idematapp2020, the 'gate', that is where the material is assumed to be, is the port of Rotterdam (Vögtlander 2020). Therefore, only the transport leg from the Port of Rotterdam to the factory needs to be added for the transportation of raw materials. However, for bulk materials with a high density, this transportation leg can be neglected for short distances (Vogtländer 2015).

One example:

If we assume that 1 kg bulk plastics is transported over 100 km, then the carbon footprint will be small compared to the material burden:

- *Transportation gives 0.0084 kg CO2E per kg material per 100 km (standard European truck + trailer)*
- *Material burden gives 2.12 kg CO2E per kg material PET polymer pellet production, Idematapp2020*

Thus the contribution of transport yields 0.4% of the material burden, per 100 km.

Especially in the competitive market of raw materials, redundant transportation is tried to be minimized, to save costs. Considering the locations of the direct suppliers (mostly in north western Europe) and the factories that produce intermediate goods from the bulk materials, the average traversed distance for bulk materials is likely to be less than 1000 km. Therefore, the contribution of this transport leg is cut-off. (< 5 % of the total carbon footprint of the mattresses).

5.2.2 Transport of components and semi-finished components

The transport of components and semi-finished products account for a great part of the total transportation carbon footprint. This can be explained by three aspects:

1. There is a great number of components, that all need to be transported.
2. Most components and half-fabricates transported in this study are textile or foam materials, with rather low densities. They take a relative large amount of space per kg material.
3. Auping follows the just-in-time principle, that aims at the reduction of stock levels before and after production. This method is more extensively explained in Section 5.2.3.

As a consequence, the transport of components from the suppliers to the manufacturer is analysed more intensively. All suppliers are located in Europe. Auping actively tries to have a supplier base nearly to its production facility. Therefore, most suppliers are located in or closely to the Netherlands. In Table 97 of Appendix 16, the assumed distances traversed for component transport are given. These are calculated by taking the "shortest road" option in google maps.

5.2.3 Transport of new mattresses

The transportation of new mattresses can be divided into two legs:

- The transport from the factory, to retail points.
- The transport from the retail points to the customers.

After a customer ordered a specific mattress from Auping, a request is send to the factory to start production for this mattress. Auping produces according to the Just-In-Time production principle. This is a logistic method, whereby goods are brought to the subsequent station, at the exact time these are required. Therefore, the production of mattresses starts only after an order is placed. As a consequence, suppliers are not allowed to deliver large portions of materials at once (stock), if these are not needed in the near future. By this method, stocks levels in the factory and at retail points are minimized. However, from a transportation point of view, this logistical strategy may be less efficient.

This can be explained as follows:

Auping strives to deliver a mattress within 2 weeks of production. By the just-in-time principle, there is no option to produce in advance, since the aim is to avoid stock. As a consequence, for periods with a limited number of orders, still trucks will be driven to meet the promised delivery time. In traditional make-to-stock systems, production and transport can be aligned better by the aggregation of transport; companies can deliver a greater bunch of mattresses at once (stocking at shops). As a consequence, transport at low occupancy rates can be avoided.

From all transport flows in the life cycle, most accurate data is available for the legs from Auping to the retail points. Namely, Auping tracks all truck data that is under its direct organizational control, that is the leg from Auping to retail points. Hereby, two different statistics are collected: the yearly diesel consumption and the total driven distance. In contrast to the other transport legs, the diesel consumption is used to model the carbon footprint here, as this is most direct related to the emissions.

The following assumptions are made for the modelling of this transport leg:

- According to the internal data of Auping, more or less 30 percent of all transported goods in these vans are mattresses. Therefore, 30% of this diesel CO2e is dedicated to mattress transport.
- The yearly data of Auping includes the transport to hubs for international transport of products. In this LCA, there is only focused on products sold in the Netherlands. Therefore, calculations based on these statistics can be seen as upper bound for the carbon footprint of this leg.
- *IDEMAT2020 Diesel (incl) combustion*, is used to calculate the emissions. This points includes both the production process emissions and the combustion of the diesel.

This calculation can be made more accurate in future research by incorporating the model of the truck in the calculation.

5.2.4 Transport of end-of-life

Vivo

The end-of-life phase of the Vivo starts at the disposal of a mattress at a customer. The disposal of mattresses follows often one of the following two paths:

- After a new mattress is sold, the old mattress is collected by the retailer. The retailers of Auping offer this service for free, and collects the mattresses at the customer's houses.
- A customers brings the mattress to a municipality waste collecting point.

From there, the mattresses are either brought to a mattress recycler in The Netherlands, or brought to a waste processor.

Evolve

This new mattress has been recently released, because of that the logistical system is not yet fully developed. In this section, two scenarios for the end-of-life logistics are given. First, all old mattresses of the Evolve are brought to a nearby Auping retail point[13]. From there, the mattresses are transported to the Auping factory, for disassembly. Thereafter, all textile materials are brought to a

[13] Only a limited number of old Evolve mattress are collected to date (2020), that are all products returned within the 90 days return period.

PET recycling facility and all steel parts that are not re-used, are brought to a local steel recycler. If steel springs are re-used, these are assumed to remain at the Auping facility.

The location of the PET recycling facility is not known yet. At this respect, Auping asked to define the carbon footprint for two different scenarios:

- The new mattress recycling facility is located nearby Aupings production facility in Deventer.
- A recycling facility in Austria (Starlinger) is used for recycling.

Thereafter, the recycled PET is supplied directly to the different component suppliers. Besides, all recycling waste (1- recycling rate), is assumed to be brought to a local waste processes.

5.3 Modelling of the transport flows

In this section, the method to model the transport in the life cycles is explained. First, all related transport parameters are briefly discussed. Then, two formulas are given that are used to determine the carbon footprints of the flows. Lastly, flow schemes are given of both life cycles, with the carbon footprints for each flow.

5.3.1 Parameters for transport

The carbon footprint for each transportation mode is modelled by use of generic transportation data. The Idematapp2020 database provides a list of inventory data for frequently used transportation modes. In Table 25, some of the relevant inventory rows for this study are mentioned. To use this data adequately, five aspects of the transportation are required:

1. The transport mode (E.g. truck, train, vessel).
2. The volume of the transported goods (including the efficiency of packaging).
3. The weight of the transported goods.
4. The occupancy rate of the truck.
5. The transport distance.

These points will be addressed in the next sections.

Description	Unit	Restriction
Idematapp2020 Truck+container, 28 tonnes net	*tkm*	(min weight/volume ratio 0,41 ton/m3)
Idematapp2020 Truck+trailer 24 tonnes net	*tkm*	(min weight/volume ratio 0,32 ton/m3)
Idematapp2019 Truck+container, 28 tonnes net	*m3.km*	(max weight/volume ratio 0,41 ton/m3)
Idematapp2019 Truck+trailer 24 tonnes net (m3.km)	*m3.km*	(max weight/volume ratio 0,32 ton/m3)

Table 26. Inventory data rows used in this study

5.3.2 Transport modes

In the life cycles of mattresses, various transport modes can be used. In Table 26 the transportation modes for different transport flows are given. Except the raw materials, all flows are realized by trucks. These trucks are not similar, the involved trucks have different load capacities and functionalities (with trailer or with container). Therefore, the most suitable row of the Idematapp2020 database is chosen to model the transport flows. However, for some of the instances, the tonnage of the trucks deviates significantly from the listed exemplars. For these cases, additional truck inventory points are approached based on fuel consumption estimates. In Appendix 15, the derivation of these new inventory points can be found.

Transported flow (material form)	Transport mode/ vehicles
Raw materials	Vessel, truck, pipes, train
Semi-finished goods	Trucks
Components	Trucks
New mattresses	Trucks
Old mattresses	Trucks
Wastes	Trucks
Recycled material	Trucks

Table 27. Transport modes per transport flow for the systems (identical for both)

5.3.3 Volume or weight

For various inventory data rows in the Idematapp2020, an extra restriction is given: a weight/volume ratio limit. Depending on this weight/volume ratio, the unit is either per ton.km, or per m^3 km. This relates to the fact that a truck load is restricted by two factors:

- *Weight restriction*: What mass is allowed to transport
- *Volume restriction*: How much Volume fits in the truck

What is dominant for a certain load, depends on the weight/volume ratio of the goods. Lightweight materials such as fabrics, hollow parts and cardboard boxes have a relatively high space occupation per kilo. Therefore, a greater number of trucks are required to transport a given weight of these materials, compared to more dense materials such as bulk plastics. The same applies for materials that are extremely dense, as trucks are as well restricted by a maximum weight load. In the right column of Table 25 these restrictions are given for the listed data points. An inventory row should only be used if the transported weight/volume ratio fits the given limits. One example:

Database row: "Idematapp2020 Truck+trailer 24 tonnes net (max weight/volume ratio 0.32 ton/m3)"
This row shall only be used if the weight/volume ratio is smaller than 0.32 ton / m3.

Therefore, for all transported loads in this study, first an estimation of the weight/volume ratio is made. To define the right weight/volume ratio for the transported loads, the packaging method is as well considered. This is explained in the next section.

5.3.4 Packaging volume efficiency of transported goods

Many of the components in the mattresses are packed in an inefficient manner. More trucks are required to bring certain amount of inefficiently packed goods. Two examples:

- Cardboard packages often enclose significant loose spaces, that cannot be used for transport of other products. From a space efficiency perspective, plastic sealing may be a better solution.
- The pocket springs are delivered on a roll, placed on a pallet see Figure 44f. The pallet space cannot be used by other goods. The space between the rolls, the light grey area in Figure 44 d, is lost as well.

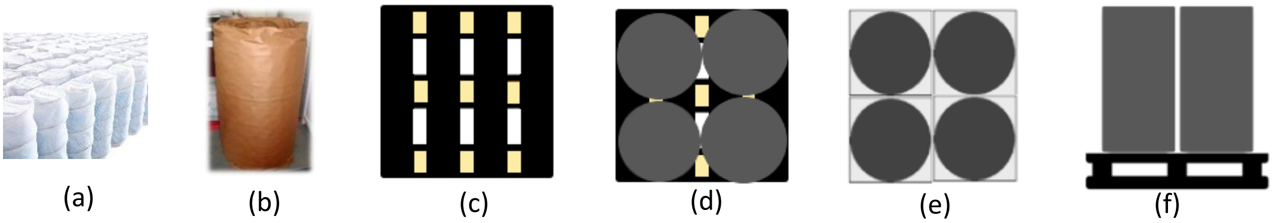


Figure 44. The transportation method of pocket springs. Figure a and b show the pocket springs, and the pocket springs compacted on a roll respectively. Figure c and d show how the rolls are packet on a pellet. In Figure e, the light grey area describes the 'loose space' by this packaging method. In f, redundant space the pellet takes can be seen.

The packaging volume efficiency can be used to obtain a more accurate estimation of the transported burden. The packaging volume efficiency is defined as follows:

"The volume percentage of a transported good that is taken by the main product".

In other words, if a roll of fabric has a size of 0.70 m3 and the packaging is 1 m3, the packaging volume efficiency will be 0.70/1 = 70%.

For all transported goods in this LCA, an estimate of the packaging volume efficiency is made. This factor, always smaller or equal to 1, is multiplied to the density of the transported goods to obtain the weight/volume ratio, see formula 9. Similarly, the weights of the packaging could be included too, for the transportation of dense materials. However, this contribution is assumed to be neglectable for now. In Appendix 19, the approximation method for other relevant packaging forms for this LCA are explained.

$$r_t = \eta_t \frac{m_m}{v_m} \quad (9)$$

Where

r_t = *The weight/volume ratio for the transported goods t (-)*
η_t = *The packaging volume efficiency, volume efficiency percentage (-) of transported goods t*
w_t = *The weight of the transported goods t (kg)*
v_t = *The volume of the transported goods t (m3)*

5.3.5 Occupancy rate of trucks

Ideally, trucks will drive only when they are full; no extra goods can be loaded into the truck. However, depending on the size, timing and requested delivery date of orders, trucks drive with partially 'left over' capacity. Therefore, another factor that impacts the transportation burden, is the occupancy rate. In this thesis, the occupancy rate, is defined as follows:

The share of a truck load used, against the left over capacity.

In Figure 45 this definition is explained by an example, representing an occupancy rate of more or less 67%. The loose spaces between the rolls of fabric in this picture are not considered in this number, as these are taken into account for the packaging volume efficiency. The Idematapp database assumes an occupancy rate for trucks of 100% for the transport first leg and 0 % (empty) for the return leg. As a consequence, this inventory value should be divided by a number smaller than one, for lower occupancy rates. (Vogtländer 2015).

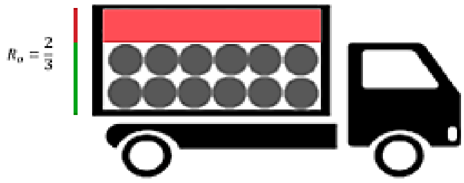


Figure 45. Example for occupancy rate of 67%

For all transport flows an occupancy rate is estimated. These values are based on interviews with logistics personnel of Auping and retail points. Due to the 'Just in time production' principle of Auping for all her production activities, suppliers can optimize their transport of components to a lesser extent. Eventually resulting to lower occupancy rates of their trucks.

5.3.6 Distances

To estimate the carbon footprint of a certain transport flow, the traversed distance is required. However, due to practical reasons, the actual distance cannot be defined for most flows. Therefore, for each distance, an educated guess is made. In Appendix 14 , these values are given including a short explanation of the applied approximation method (the reasoning).

5.3.6.1 Haversine's formula

For several transport flows, no accurate distance data is available, and the average distances cannot be estimated easily, this is especially the case if an average needs to be taken over many optional locations. For example:

Mattresses can be brought to over 800 different waste collection points in the Netherlands. From here, these can be brought to one of the 12 waste processing points. How can the average distance a mattress traverses from waste collection point, to waste processing points be estimated?

To approach the distance between coordinates on a flat surface, Pythagoras can be used. However, this 2-dimensional triangular approach, will not be accurate for distances on a globe (earth). For these cases, Haversine's formula can be used to estimate the distances. This formula determines the shortest distances between coordinates (longitude and latitude), on a spherical surface. In Appendix 17, this formula is further explained. As input for this formula, the coordinates from an open source list of all streets in the Netherlands (over 200.000), are used.

The following steps are applied to approach the average traversed distance:

1. A list of destination points is selected from the full list of addresses.
   E.g.: The 12 waste processing locations in the Netherlands.
2. The distances from all streets (the 'from' locations) in the list to all these destination points is calculated with Haversine's formula.
   E.g.: The linear distances from the Spoorkade in Kampen, to all 12 waste processing points are: (110, 50, 69, 69, 82, 151, 130, 135, 78, 79, 76, 117 km)
3. For every street in the lists, the minimal distance to all destination points is selected.
   E.g.: The minimal distance selected is 50 km; from the Spoorkade in Kampen to the waste processing point at the Beilerweg in Wijster .
4. Now the average minimum distance from all streets in the list, to the destination points is determined.
   The average linear distance from any street in the Netherlands, to its nearest waste processing point is 30 km.
5. Lastly, the average road distance is estimated, by multiplying this number by 1,2. This "road distance/ linear distance" ratio is estimated by dividing 20 road distances obtained by Google Maps, by the linear distances between those points in the list.
   The average road distance from any street in the Netherlands, to the nearest waste processing point is more or less : 30 x 1,2 = 36 km. This can be used as estimate for the average road distance between the waste collecting points and the nearest waste processor.

To decrease the required computational effort, the list of 500.000 streets is reduced first. This is ought to be done at random. By use of the filter function in excel, this list is reduced to roughly 27500, only including the postal codes ending at (AA - AZ). This is reduction is realized using the filter function in excel. in the example, the distance from *all streets* to *nearest waste processing points* is assumed to be similar, to the distance between the *waste collection* and *nearest waste processing points*.

Some remarks for this method:

- The population density is not taken into account. Short streets with only a few addresses count as heavy as long streets with more than 100 addresses.
- In order to use this method conveniently, the destination lists needs to be of limited size. Otherwise, the computational effort will increase rapidly.
- The ratio "road distance/linear distance" depends on the road infrastructure of that area. For areas with a low road density, this ratio may be higher.

5.3.7 Carbon footprint of transport flows

Summarizing, for all transport flows in the systems, first the most suitable inventory row for the specific transport mode is selected. Depending on the weight/volume ratio, either a weight (in tonnes), or volume (in m^3) is required to model the transported amount. Then, an estimation of the occupancy rate of the vehicle is made. If the load is expressed as a volume, the packaging volume efficiency is estimated as well. Lastly, all obtained factors are multiplied by the traversed distance. Therefore, formula 10 is used for all cases that use the unit *t km,* and formula 11 is used for all instances in *m^3 km*.

$$C_f = \frac{m_t}{o_f} i_f d_f \qquad (10)$$

$$C_t = \frac{m_t}{r_t} o_f i_f d_f \qquad (11)$$

Where

C_f = Carbon footprint of the selected transport flow f (kg CO2e)

m_t = Mass of the transported goods t (kg)

O_f = Estimated occupancy rate of the vehicle, for that specific flow f (-)

i_f = Inventory data point for that flow f(kg CO2e/ t.km)

d_f = The traversed distance for leg (km)

r_t = The weight/volume ratio of goods t (kg/m3)

5.3.8 Transportation flow schemes

As a consequence, for all transport flows in the life cycle, a carbon footprint is found. However, short distance transportation within plants or between nearby plants (<5 km), are assumed to yield a negligible burden and are therefore cut-off this analysis. A schematic representations of the transportation flows within the Vivo and Evolve mattress are given in Figure 46 and 47, respectively (on the next pages). The numbers near the flow denote the estimate of the carbon footprint. Table 27 and 28 give the assumed numbers for the occupancy rate and the packaging volume efficiency (on the next pages).

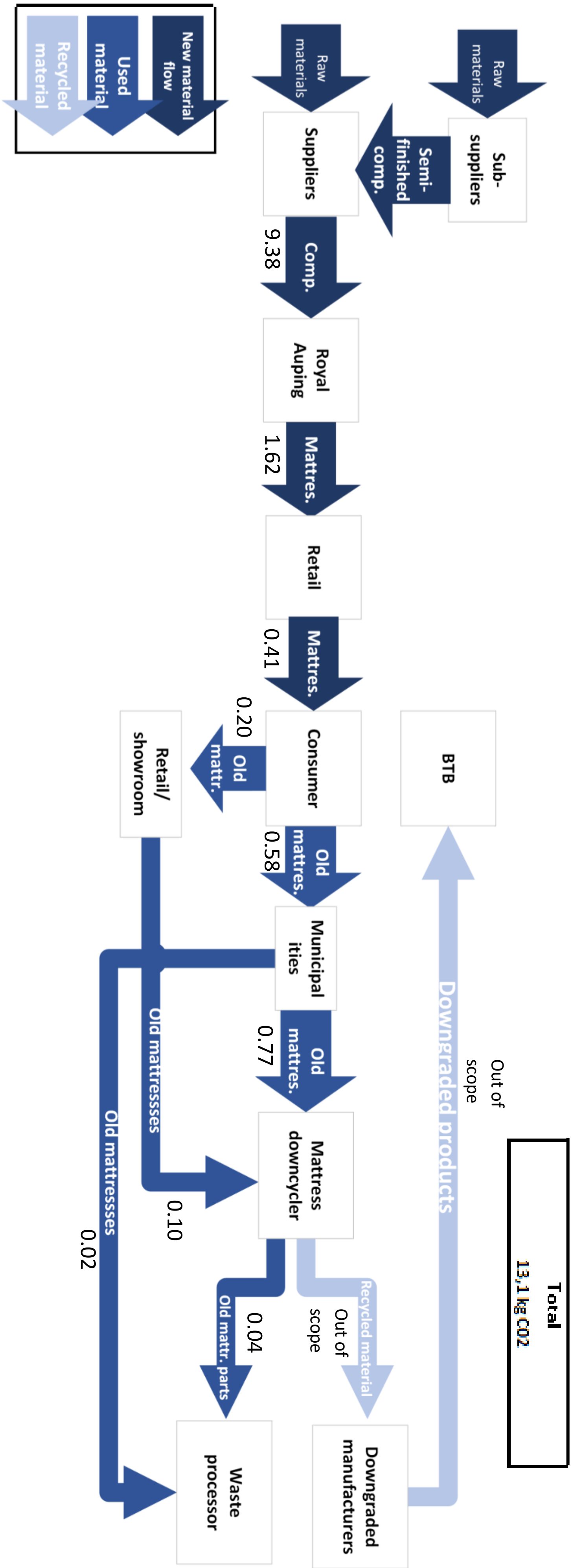


Figure 46. The transportation flow scheme of Vivo

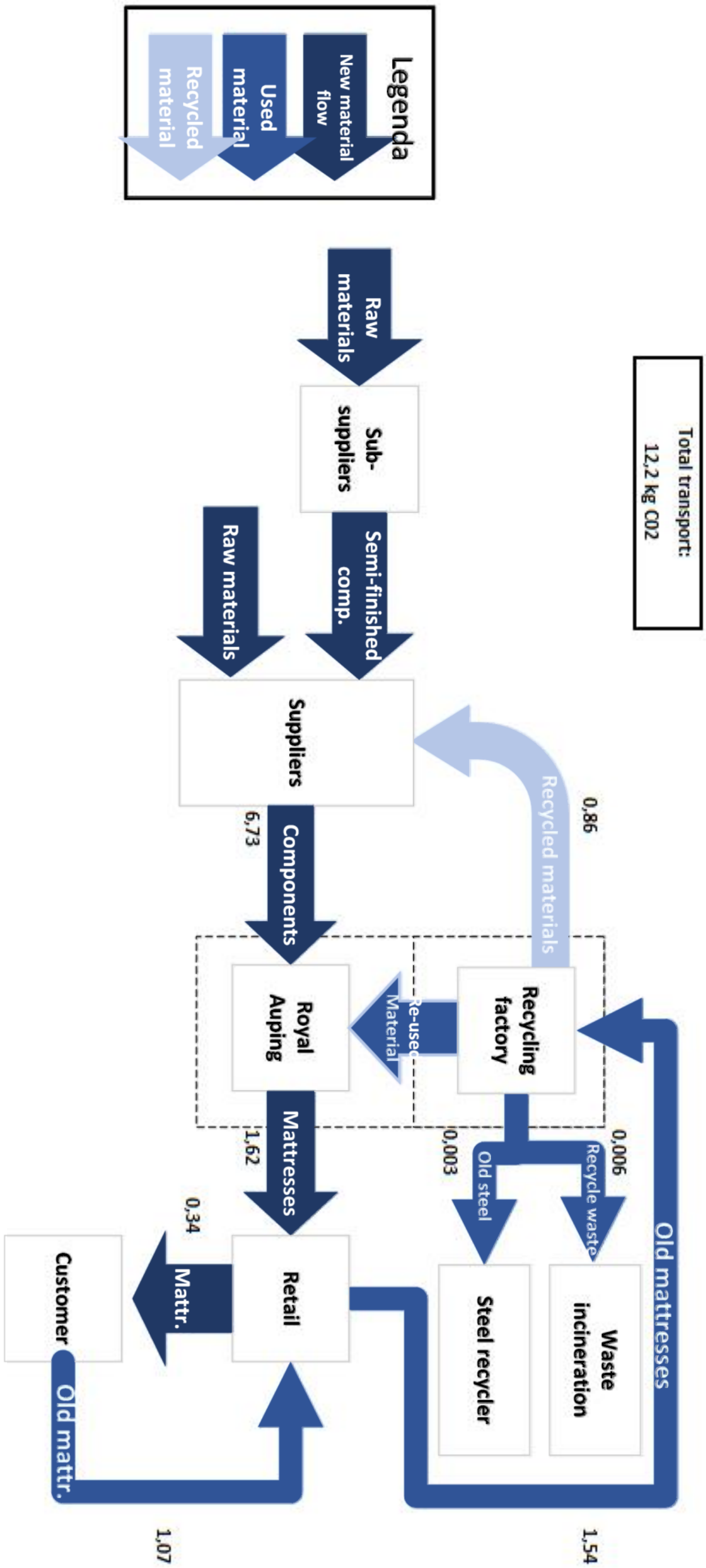


Figure 47. Transportation flow scheme of the Evolve

Vivo			Vehicle burden			efficiency	
Transport material and (flow)	Kg CO_2e/ FU per flow	Distance (km)	Transport vehicle	CO_2e per unit	unit	Packaging volume efficiency	Occupancy efficiency
Raw materials	Already included in standard data	-	-	-	-	-	-
Components	9.38		Truck + trailer 24 tonnes	*0.027* *0.084*	*kg CO2e/ m3 km* *kg CO2e/ t km*	varies	varies
Auping (retail mattresses)	1.62		Diesel including combustion	*3.7*	*kg CO2e/ kg diesel*	-	-
Retail (customer mattress)	0.41	15	Lorry 3 tonnes (m3 km)	*0.13*	*kg CO2e/ m3 km*	90%	70%
Old mattresses (customer-Municipalities)	0.58	5	car	*0.13*	*kg CO2e/ m3 km*	90%	70%
Old mattresses (customer - Retail)	0.18	15	Truck 12 tonnes (m3 km)	*0.04*	*kg CO2e/ m3 km*	90%	70%
Old mattresses (Retail -	0.10	36	Truck + trailer 24 (m3km)	*0.04*	*kg CO2e/ m3 km*	200%*	100%
Old mattresses (Municipalities – Mattress downcycler)	0.77	75	Truck + trailer 24 tonnes (ton km)	*0.084*	*kg CO2e/ t km*	100%	70%
Old mattress parts (Mattress downcycler - Waste collector)	0.04	48	Truck + container 28 tonnes net (ton km)	*0.072*	*kg CO2e/ t km*	100%	100%
Old mattresses (Municipalities - Waste processor)	0.02	15	Truck + trailer 24 tonnes (ton km)	*0.084*	*kg CO2e/ t km*	100%	100%
Total end-of-life	**1.72**						
Total	**13.13**						

Table 28. The inventory data for transporting Vivo mattresses

Evolve (recycling at Auping | recycling in Austria)			Vehicle burden			Efficiency	
Transport material and (flow)	Kg CO_2e/ FU	Distance (km)	Transport vehicle	CO_2e per unit	unit	Packaging volume efficiency	Occupancy efficiency
Raw materials	Already included in standard data	-	-	-	-	-	-
Semi-finished and finished components	**6.73**		Truck + trailer 24 tonnes	0.027 0.084	kg CO2E/ m3 km kg CO2E/ t km		
New mattresses (Auping retail)	**1.62**		Diesel including combustion	3.7	kg CO2E/ kg diesel		
New mattresses (Retail - Customer)	**0.34**	13	Lorry 3 tonnes (m3 km)	0.13	kg CO2E/ m3 km	90%	70%
Old mattresses (Customer - Retail)	**1.07**	13	Lorry 3 tonnes (m3 km)	0.13	kg CO2E/ m3 km	90%	70%
Old mattresses (Retail - Auping)	**1.54**	62	Truck 12 tonnes (m3 km)	0.04	kg CO2E/ m3 km	90%	70%
Old mattress (Auping - Recycler)	**0 | 8.43**	0 | 1080	Truck + trailer 24 (m3km)	0.04	kg CO2E/ m3 km	200%*	100%
Secondary PET (Recycling factory -suppliers)	**0.86 | 1.04**	Various	Truck + trailer 24 tonnes (ton km)	0.084	kg CO2E/ t km	100%	70%
Old steel (Recycling factory - steel recycler)	**0.0029**	5	Truck + container 28 tonnes net (ton km)	0.072	kg CO2E/ t km	100%	100%
Recycle waste (PET mix)	**0.040**	48	Truck + trailer 24 tonnes (ton km)	0.084	kg CO2E/ t km	100%	100%
Total end-of-life	**3.25 | 11.81**						
Total	**12.2 | 20.9**						

Table 28. The inventory data for transporting Evolve mattresses

6 Interpretation of results, sensitivity analysis

In the first section, the sensitivity and uncertainty analysis for this specific LCA is discussed. Then, the

The LCA Interpretation phase will be discussed in this chapter. Hereby, the results from the LCI and LCAI are evaluated and, based on the data, conclusions are drawn.

This part is divided into three parts:

1. The life cycle of the Evolve
2. The life cycle of the Vivo
3. The life cycles compared

Therefore, the following research questions will be answered in Part 1 and 2:

- What is the recycling potential of the Evolve, based on the first tests?
- What cost savings can be expected by recycling of the Evolve
- What is the carbon footprint of the conventional mattress Vivo?

In part 3 the following questions will be answered:

- What would the carbon footprint be for both mattresses for full waste incineration?
- What carbon footprint can be expected for the Evolve, assuming various scenarios?
- What parts in the life cycle of the mattresses contribute most to the carbon footprint?
- What are the practical advantages and disadvantages of each alternative?

The **interpretation** phase of a life cycle analysis can be defined as follows:

"*The findings of the life cycle inventory analysis, or the life cycle impact assessment, or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations*".

(ISO 14067:2018 sd)

6.1 Sensitivity analysis and of the LCA model

In LCA studies, sensitivity[14] analyses are frequently performed to point out the variation in results for changes in the input data (Bisnella et al., 2016). Sensitivity analyses are described in ISO (ISO 14067:2018 sd) as follows:

The sensitivity analysis in this LCA will support two purposes:

1. **To evaluate results for various scenarios**:
   Strategic and tactical decision making can be strengthened by quantitative support. Especially, the variables that are under direct control of the management team, are relevant to analyse.
2. **To asses sensitivity of the model regarding uncertainties:**
   A frequently recognized issue of life cycle assessments, is the lack of robustness for the outcomes (Herrmann et al., 2014), (McKone et al., 2011), (Weidema 2009), (Baek et al., 2018).
   If there are multiple modelling options for certain aspects of LCAs, (such as the end-of-life of the Vivo mattress), these can all be evaluated as scenarios. As a consequence, potential bias by modelling decisions can be minimized.

6.1.1. Uncertainties of results.

One of the great challenges of LCAs is to deal with uncertainties. In Section 4.9, there is elaborated more on this point. An indication of the uncertainty (range) for the obtained results can support meaningful decision making. Therefore, for the most important results in the next sections, an indication of the uncertainty range is given by an error bar. The area between the brackets represent an estimate for the 95% confidence interval. In other words, 95% of the values can be, with reasonable certainty, expected between these brackets. However, since the uncertainties are gathered by a qualitative approach, these interval boundaries should be seen as a rough indication rather than exact numbers.

> ***"Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a carbon footprint study".***
>
> (ISO 14067:2018 sd)

[14] In literature, sensitivity analysis and scenario analysis are used interchangeably.

6.2 Part I The circular mattress : Evolve

The new circular mattress will be evaluated first. In this section, the following aspects are discussed:

- The CO2e burden of the individual recycling processes
- The effect of the recycling rate on the carbon footprint of the mattress
- Various scenarios for the end-of-life
- The effect of recycling in Austria on the carbon footprint (additional transport carbon footprint)
- The amount of recycled content in mattress in relation to sales

In the current phase of development of the Evolve mattress, its life cycle is not yet fully defined. The material inflow and supplier processes are yet organized, but the manufacturing process at Auping and the recycling process (end-of-life), are still under development. As there are many options to evaluate, some specifically chosen scenarios are highlighted in this section. In case of the circular Evolve mattress, these scenario's involve the transport phase and the end-of-life phase of the mattresses, as these are not fully determined yet.

6.2.1 End-of-life process Evolve, defined by testing

The recycling process is essential for the circular concept to become a success. Both the effectiveness of waste handling and the material quality of new obtained products, depend on this process. Closed loop recycling of textile, is still in a pioneering phase. As a consequence, results of similar recycling cases, are scarce or unavailable. Most likely, the complete development phase of the recycling process will take several more years. In the current phase testing is done and first results are obtained. These first results provide a first indication of the potential recycling benefits. Figure 48 shows the carbon footprint of these recycling processes, Figure 49 the material efficiencies.

Recycling steps

A more elaborative explanation of these processes can be found in Section 4.6. In the current section, every step and the related tests are briefly discussed.

Disassembly: After collecting the Evolve mattresses from customers, these are disassembled. For the disassembly process, tests on different scales were executed, two are included in this LCA. The first test consisted of a small test in which a small slice of the mattress was heated in a very compact oven. Subsequently, the second test was executed which was a full scale tests is, in a conveyor oven.

Recycling: After disassembling, the materials are recycled together with the post-industrial material flow. For now, mechanical recycling seems to be the most promising recycling method. Therefore, this recycling method is tested first. One small scale test (300 kg inflow material) is done at a company called Senbis. A next test, on a more realistic scale, with 1000 kg inflow material is executed at Starlinger. The results of both are evaluated in this LCA. These companies did indicate a material recycling efficiency that is displayed in Figure 49.

Polycondensation: is a process done to get the granulate quality at the desired grade after the extrusion process, which is tested at Senbis. The material efficiency of this test is used in this LCA. However, there is no energy data available for this test. Therefore, a conservative estimation is made based on a potentially suitable machine for this specific case.

The energy consumption for the disassembly, recycling and polycondensation tests, are used to estimate the carbon footprints that are given in Figure 48. From these values, a estimation for the total carbon footprint of the recycling process is made. The most right bar chart shows this estimation, that is composed of:

- The conveyor oven test for disassembly
- The Starling test for recycling
- Polymerization test based on technical specifications of a potential machine.

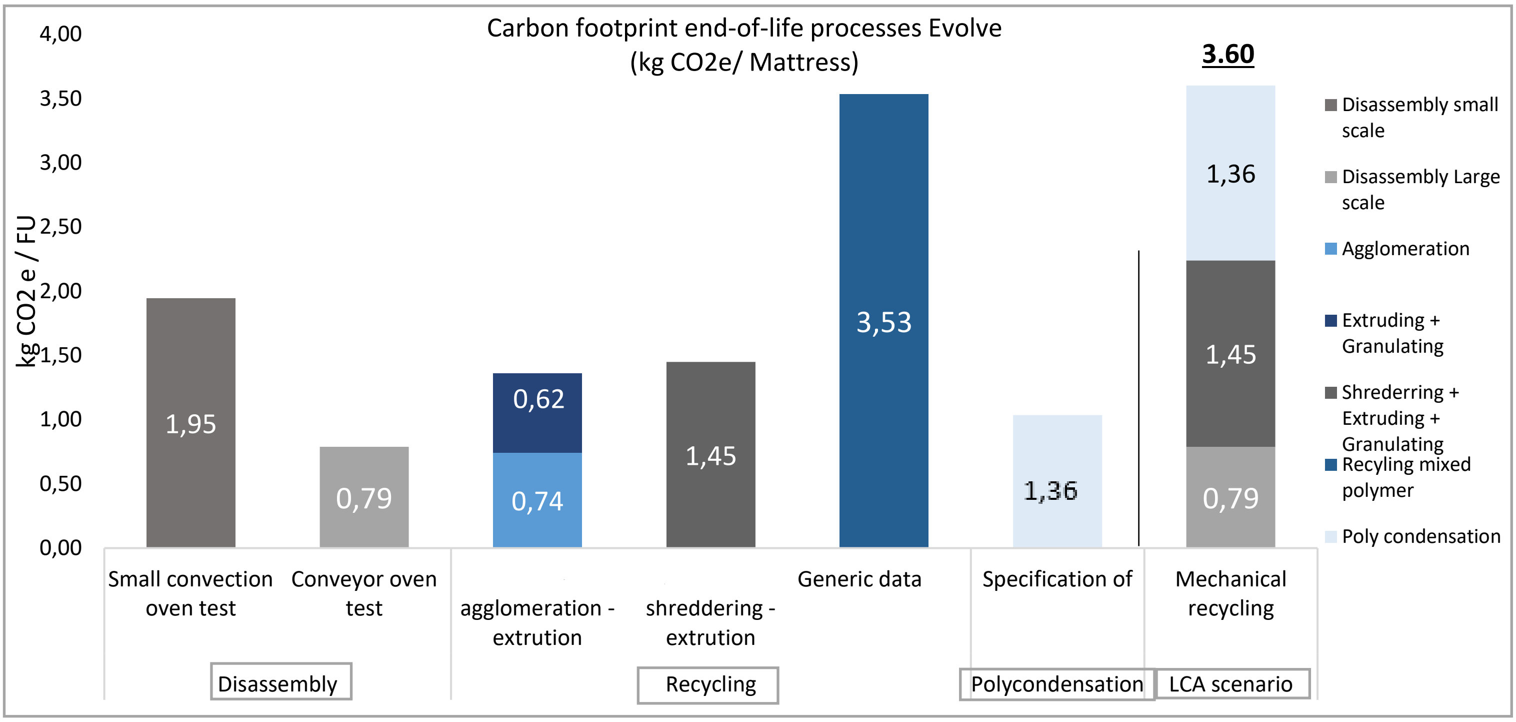


Figure 48. The carbon footprint of different recycling processes and the assumed scenario for this LCA (most right)

Conclusions:

- The total recycling[15] carbon footprint of the combined scenario is 3.6 kg CO2e per FU (per mattress), the material efficiency is estimated conservatively at 89% (a multiplication of the polycondensation and extruding efficiency).
- Extruding and polycondensation seems to have the largest contribution to the carbon footprint.
- The results are merely based on rough testing and should be only used indicative. Therefore no uncertainty range is given, as this could give a false sense of accurateness.
- The total carbon footprint of recycling seems to be more or less equal to the generic data situation.

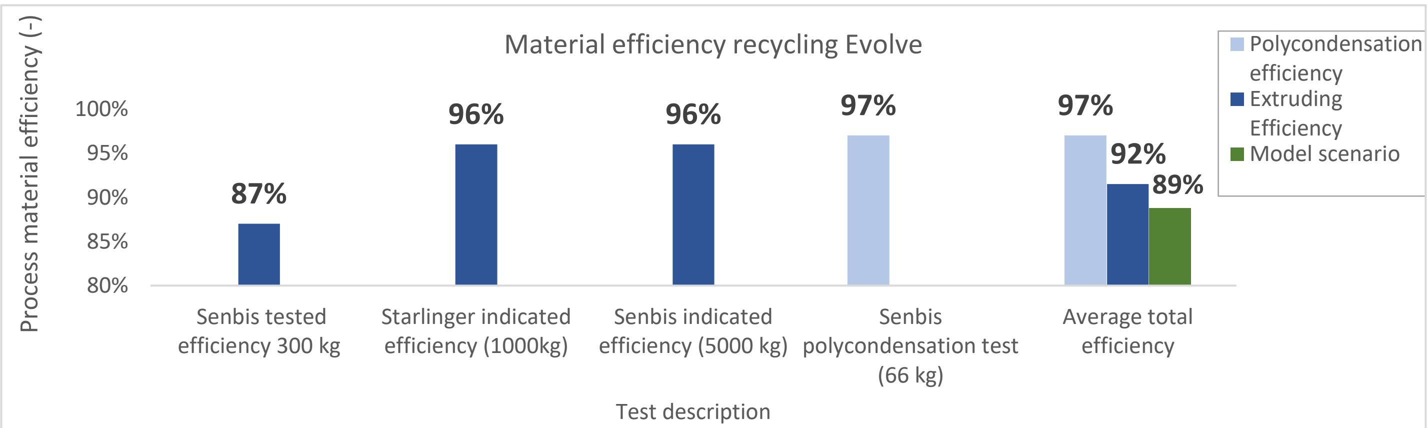


Figure 49. The material efficiencies for the different recycling processes. The average total of 89% is used in this chapter

[15] From this point on, by the recycling process, disassembly, recycling and polycondensation togheter is meant.

6.2.2 End-of-life process Evolve, benefit of recycling against waste incineration

Recycling is only beneficial if the benefits of these processes exceed the costs. This applies both for from an economical and environmental point of view. For the carbon footprint, the recycling burden and benefits are as follows:

Recycling burden *the carbon footprint "costs" of recycling* **:**

- Recycling process energy (including disassembly and polycondensation)
- Additional transport for recycling

Recycling benefit *the carbon footprint "savings" of recycling***:**

- Incineration emissions prevented
- Saved on virgin material

In Figure 50, these burdens and benefits are given, for the mechanical recycling case of the Evolve. Hereby, a recycling rate of 89% is assumed. The recycling waste (11%) is assumed to be incinerated. The bar "netto benefit", describes the benefit of recycling against waste incineration. Thus, the sum of the saved virgin material, the prevented incineration and the recycling process energy.

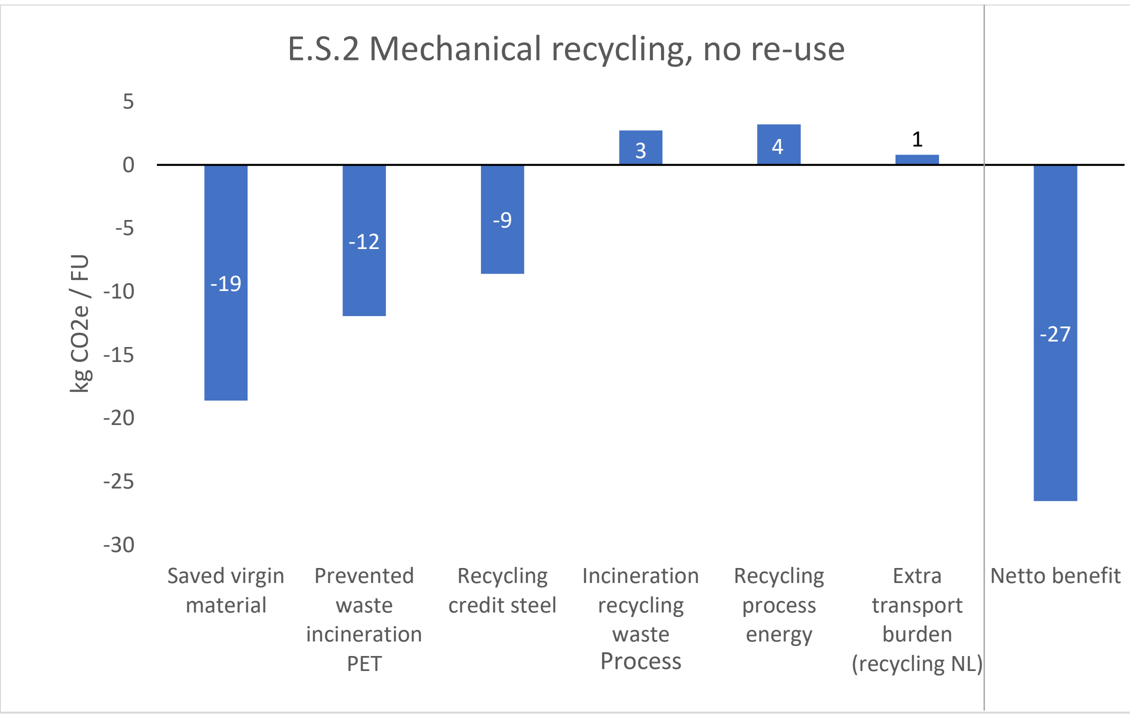


Figure 50. The benefits of mechanical recycling.

Conclusions:

- Most emissions are avoided for production of virgin materials, 19 kg CO2e per mattress.
  This is similar to an alternative research: 18 kg CO2e (Epea GmbH 2020)
- 12 kg CO2e is prevented for waste incineration.
- The netto benefit of PET recycling instead of waste incineration is 27 kg CO2e.
  Saved virgin material + prevented incineration – recycling process energy – extra transport[16]

[16] The recycling credit for steel is not included in the metto benefit, as steel is collected from the ashes after incineration and recycled as well (A.E.B Amsterdam 2020).

6.2.2. Sales and recycled content of the circular mattress

The amount of recycled PET in the mattresses depends on the recycling rate. However, there should be enough old material available to recycle. The common lifetime of mattresses is ten years. Therefore, for the first years after the release of the Evolve mattress, the flow of returning mattresses will be limited. For these early years, more or less all recycled content in the mattresses is coming from post-industrial (P.I.) wastes.

In general, the amount of recycled PET content in the mattresses depends heavily on four factors:

1. The recycling rate; material losses by recycling and polycondensation and potential mixing in virgin material (to obtain the right quality).
2. The number of mattresses sold more or less a decennium before.
3. The number of mattresses sold now.
4. The amount of P.I waste.

Hereby, the assumption is made that all mattresses are recycled shortly after the disposal. Furthermore, for this closed loop system, 100% of the circular mattresses sold are assumed to be returned to the company. The estimated amount of P.I waste at Auping is used as input only, no waste at suppliers is taken into account. Figure 51 shows the amount of recycled PET in the mattress for a certain "sold mattresses" – "disposed mattresses" ratio. This ratio can be interpreted as follows:

If at a certain moment for every 7 sold circular mattresses, 10 mattresses are disposed, the assumed share of recycled content in the mattress is 82%. Determined by the flow of recycled granulate (old mattresses and P.I waste), against the sales.

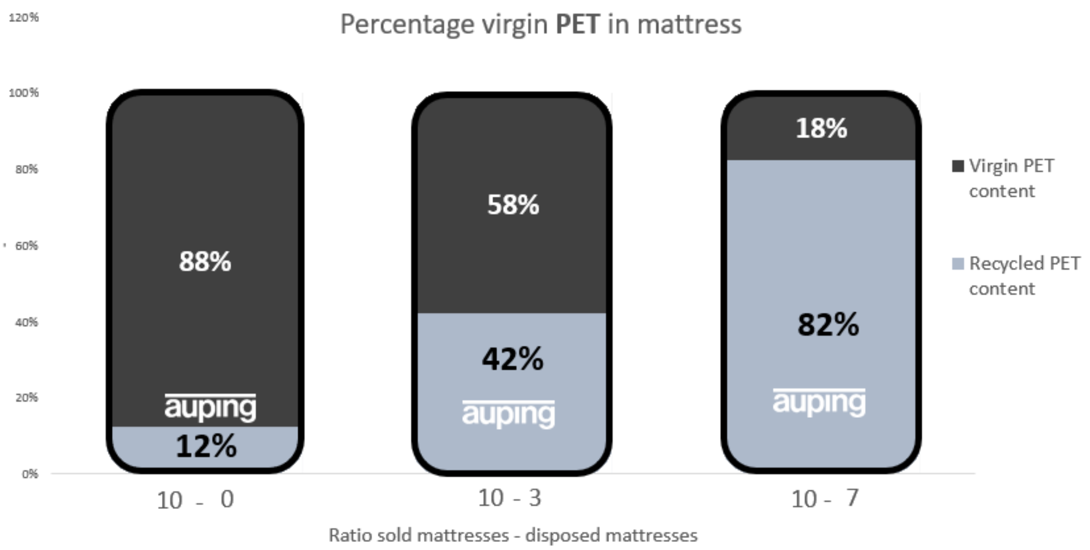


Figure 51. The percentage virgin PET against the recycled PET in the Evolve for sales – disposed ratios

Evaluation

This ratio is essential for a stable and feasible business proposition, for various reasons. First, recycling is expected more affordable for larger volumes. If the company invests in an in-house machine, this investment will be made against a certain pay-back expectation. In case these volumes remain low, the invested money per kg recycled material will be high. If external capacity is used for recycling, costs may increase as well for smaller volumes by the principle of economies of scale[17]. Secondly, the recycling efficiency is assumed to decrease for smaller amounts. The changeover between different inflow materials, always yield a certain loss of material. This loss is relatively smaller for small volume runs (Senbis 2020). Thirdly, a constant flow of recycled granulate is essential for a stable supply chain. A stable and predictable supply of secondary material is essential for an effective collaboration, for purchasing and logistical reasons. In all results for the Evolve in this thesis, an equal inflow and outflow of mattresses is assumed, unless specified differently.

Conclusions:

- For the first after released, the recycled content in mattresses will be mainly of P.I waste origin. The remainder will be virgin content.
- If the P.I waste of suppliers is collected as well, then the amount of secondary content in the mattress will increase as well.
- If for every 10 mattresses sold, 7 mattresses are disposed, an estimated 82% of the PET in the mattresses is assumed to be recycled content
- A constant flow of secondary material can be essential for a stable business proposition.
- In this LCA, the number of disposed circular mattresses is assumed to be equal to the number of sold exemplars.

[17] Economies of scale: "A proportionate saving in costs gained by an increased level of production" (Oxford Dictionairy 2019)

6.2.3. Transport burden for different recycling locations.

In the first period, the amounts of disposed mattresses will be limited. Therefore, renting external recycling capacity may be more affordable option. The current testing on large scale takes place in Austria at a large recycling machinery seller. As this may be the potential for a recycling machine of Auping, it is interesting to know the extra transportation carbon footprint for recycling here. The effect of recycling in Austria has three extra CO2E burdens:

1. Extra transport of old mattress or P.I waste material, that is assumed to be compacted first.
2. Additional transport distance from recycler – suppliers, as most suppliers are located near on in The Netherlands.
3. (Potential) differences in carbon footprint of recycling, since the electricity mix is different in Austria than in the Netherlands.

For the first two points, the values are provided in Figure 52. The electricity mix is assumed to be not that different for both countries and is not further analysed for Austria in this LCA.

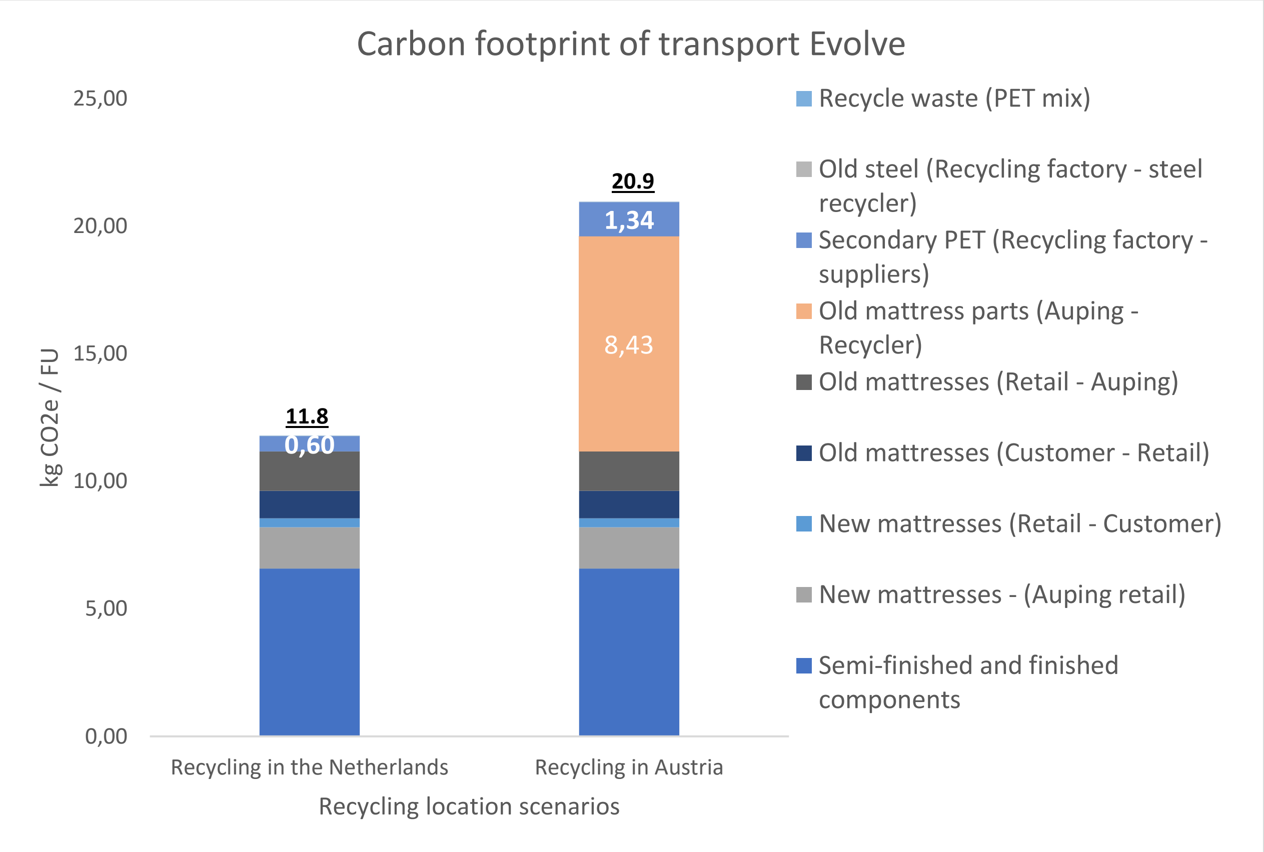


Figure 52. Carbon footprint for transport of Evolve, for recycling in the Netherlands and recycling in Austria.

Conclusions:

- If the recycling activities are moved to Austria, the additional CO2e burden is estimated at 9.2 kg CO2e/FU (per mattress).
- The transportation burden will increase from a 17% of the total carbon footprint, to 26% of the total carbon footprint. (for a mechanical recycling scenario).
- The extra burden for transport of recycling waste is limited. Hereby it is assumed that the recycling company first collects a great amount of waste, and only transports a full truck of waste. Besides, the recycling waste has a relatively high density (compared to the mattresses), so the amount of one FU (mattress) will not take a lot of truck space per kg.

6.2.4 End-of-life scenarios

The end-of-life phase in the life cycle of the Evolve, is the most important phase for the circular concept. The quality and efficiency of recycling determine to a great extent the feasibility of the circular business model. In Table 29 various scenarios for the end-of-life phase of the Evolve are listed. The carbon footprint for each of the scenarios can be found in Figure 53 For all Evolve scenario's (E.S.X) the recycling rate is defined at 89%. The derivation of this number is given in Section 4.6.

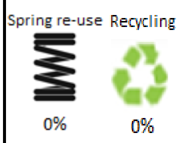
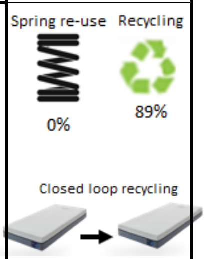
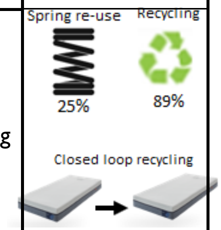
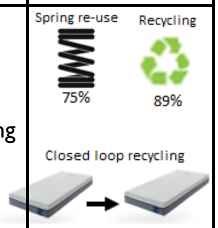
			Polymers				Steel				
	Scenario		Description	% recycling rate	% waste inc.	Sales – disposed ratio	E.o.l Steel	% recycled, market mix	Re-use of springs	Location disassembly and recycling	Icon representation
Evolve	**E.S.1**	**No recycling of polymers**	No recycling	0%	100%	*NA for "no recycling"*	Open loop recycling	44%	0%	-	
	E.S.2	**Mechanical recycling, No spring re-use**	Closed loop recycling	89%	11%	10 – 10	Open loop recycling	44%	0%	Royal Auping	
	E.S.3	**Mechanical recycling Spring re-use 25%**	Closed loop recycling	89%	11%	10 – 10	Open loop recycling	44%	25%	Royal Auping	
	E.S.4	**Mechanical recycling Spring re-use 75%**	Closed loop recycling	89%	11%	10 - 10	Open loop recycling	44%	75%	Royal Auping	

Table 29. The end-of-life scenarios for the Evolve mattress in this LCA

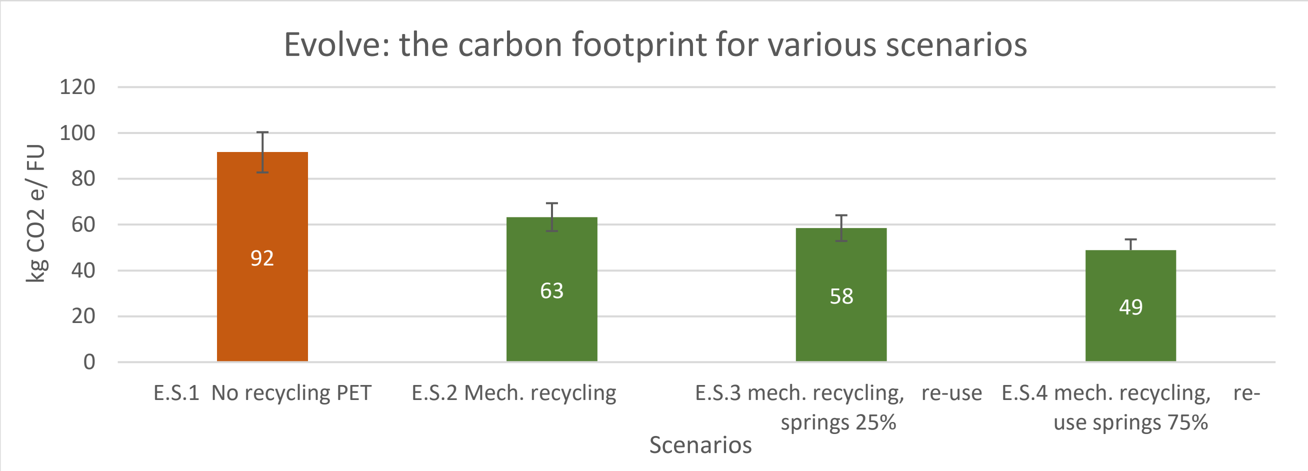


Figure 53. The carbon footprint of the Evolve for Various scenarios

Conclusions:

- For the scenario without recycling of PET, the carbon footprint of the mattress is estimated at 92 kg CO2e. The error margin is more or less 9% to both sides (+-8,8 kg CO2e).
- If at a certain moment in time, the flow of returning mattresses is closely to the number of sold items, then the carbon footprint will be more or less 63 kg CO2e per FU (mattress).
- If 75% of the pocket springs are re-used, the additional carbon footprint reduction is around 14 kg CO2e. The total carbon footprint for that scenario (E.S.4), is estimated at 49 kg CO2e.
- By taking the uncertainty into consideration, the following conclusion can be drawn: By mechanical recycling and a spring re-use of 75% (E.S.4), a potential CO2e reduction between 35% and 56% can be obtained. Figure 54, shows how these numbers are obtained.

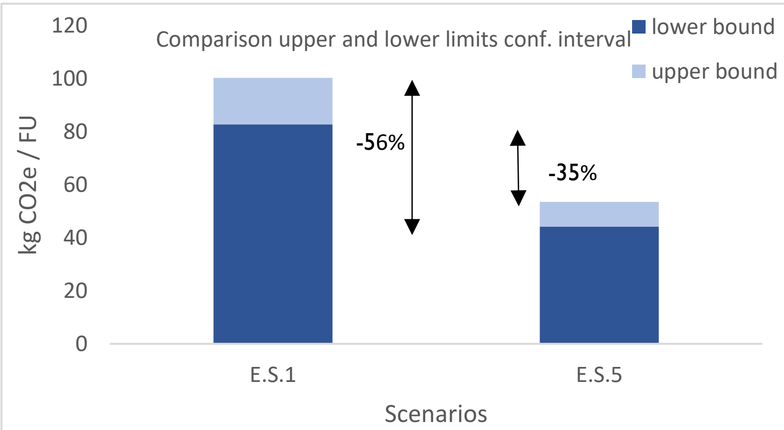


Figure 54. The uncertainty interval used to give the comparative intervals

6.2.5 The cost saving potential Evolve

Since Auping is a commercial organization, costs are a relevant factor to consider. These are out of the scope of this thesis. Nevertheless, a rough indication of the best case costs reduction is given in this section. It is important to mention that these are only savings based on the current costs, thus costs for recycling, extra transport and processes related to re-use are not considered. If these data becomes available, the netto cost savings can be calculated by the difference between the savings and the extra costs for recycling. The following assumptions are made:

- PET polyester pellet price is 978 €/ ton
  Average price PET Pellets, Europe Dec '18-'19 (Wood Mackenzie Chemicals 2019)
- Pocket spring price is roughly €28,- per FU.
  Based on internal data for a mattress of 90x210 cm (Auping 2020).
- The amount of PET that is recycled includes the wastes (such as cutting waste) in the Auping factory, but excludes the wastes at suppliers.
- The price of secondary PET is equal to that of virgin PET. The recycler obtains the same price for the secondary granulate, as it would pay for the virgin material.
- The spared costs the gate-fees are assumed to be 5€.
  The gate-fee[18] for old mattresses for the two large conventional mattress recyclers in The Netherlands. (ABN AMRO 2019).

Based on these numbers, the best case cost savings, for different recycling rates of PET and re-use rates for the pocket springs, are given in Figure 55.

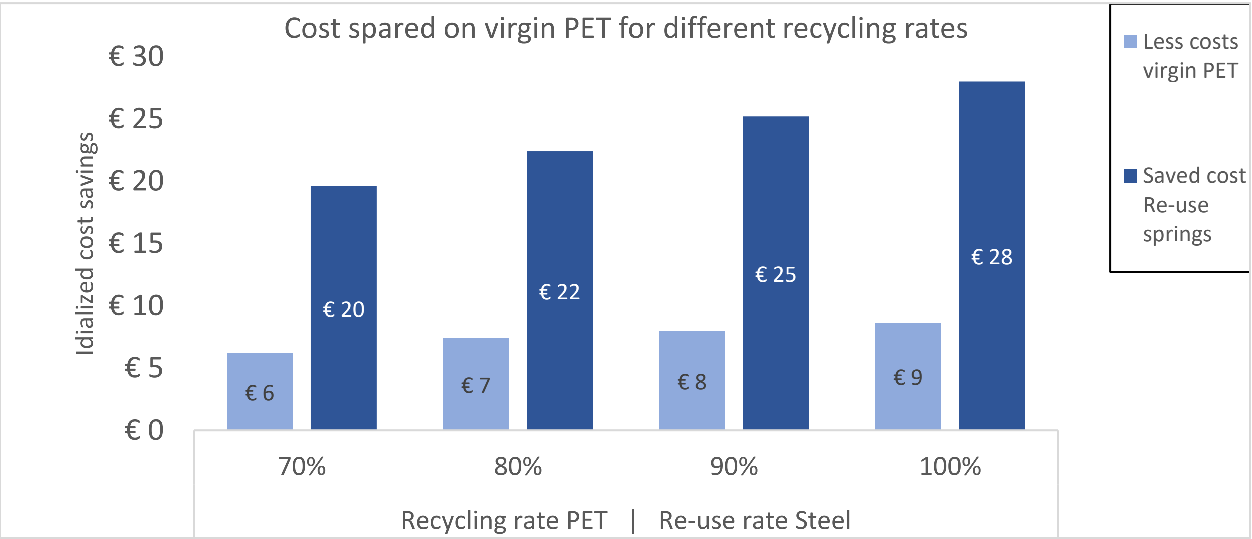


Figure 55. The cost saving potential on virgin materials for recycling and re-use, not including costs for these end-of-life processes

Conclusions:

- The most direct savings can be obtained by re-use of the pocket springs: 20€ per FU for 70% re-use. Assuming that no costly processes are get this component ready for re-use (e.g. checking, cleaning)
- The costs savings on virgin PET material would be around €8,- per FU for a recycling rate of 90%.
- For a likely scenario: 70% re-use springs, 90% recycling of PET. The estimated total cost-savings is €20 + €8 + €5 = €33,- per FU. If the total costs of recycling and re-use are lower than this value, this scenario yields a positive result in terms of costs.

[18] Gate-fees are explained in Section 4.6.1.2

6.3 Part 2: The conventional mattress: Vivo

In this section the results of the LCA for the conventional mattress Vivo are given. Hereby, first the carbon footprint is given for specifically chosen scenarios. Then the idealized case is given, in which 100% of the disposed mattresses are assumed to be recycled. Conventional refers to the life cycle of this mattress that is linear, since there is no circular flow of materials. On the contrary, there is only an extended (useful) material lifetime. An extensive explanation of the end of life of the Vivo, can be found in Section 4.6.1. In summary, there following characteristics are assumed for the end-of-life:

- One part of the disposed mattresses is collected for recycling into other products types (such as Judo tatami and insulation foam).
- From all mattresses collected by the recycler, 6% of its total mass is assumed to be rejected for recycling.
- The remainder (62%), is assumed to be incinerated without interference of the mattress recycling company.

In Table 30, these characteristics are listed. These numbers are likely to change in the (near) future. Then, the calculations shall be updated accordingly.

Assumed numbers	
Collected for recycling	38%
Not accepted for recycling; incinerated	6%
***Overall :* Recycling rate**	36%

Table 30. Vivo end-of-life key values

For the Vivo mattress, the allocation of the recycling energy burden is a source of debate in literature. The recycling energy can be allocated to:

- The primer life-cycle *The mattress.*
- The secondary life cycle *Product made of recycled material* e.g. *insulation foam.*
- Or shared between both (not applicable as A=0), see Section 4.6.

This allocation issue is discussed further in Section 4.6. In Table 30, these allocation scenarios, V.S.2 and V.S.4, are listed. The first scenario, V.S.1, denotes the situation in which no polymers are recycled[19]. This scenario can be used to see the benefit of recycling, against the situation without recycling. The carbon footprint of the Vivo scenarios (V.S.X.) in Table 31 are given in Figure 56.

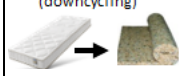
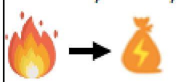
	Polymers							Steel			
	Scenario		**description**	**% Recycled mattresses**	**Recycling energy Allocation:**	**% waste inc.**	**E.o.l Steel**	**% Recycled, market mix**	**Re-use of springs**	**Icon representation**
Vivo	**V.S.1**	**No recycling of polymers**	No recycling Only waste incineration	0%	No recycling	100%	Open loop recycling	44%	0%	Waste incineration electricity recovery  100%
Vivo	**V.S.2**	**Mechanical recycling (downcycling), End-of-life = mattress**	Open loop recycling	36%	100% for the mattress, 0% for the secondary life.	64%	Open loop recycling	44%	0%	Open loop recycling (downcycling)  36%
Vivo	**V.S.3**	**Mechanical recycling (downcycling), End-of-life = 0**	Open loop recycling	36% All counted for secondary product	100% to secondary product system , 0 for the mattress	64%	Open loop recycling	44%	0%	Waste incineration electricity recovery  68%

Table 31. The end-of-life scenarios for the Vivo Mattress

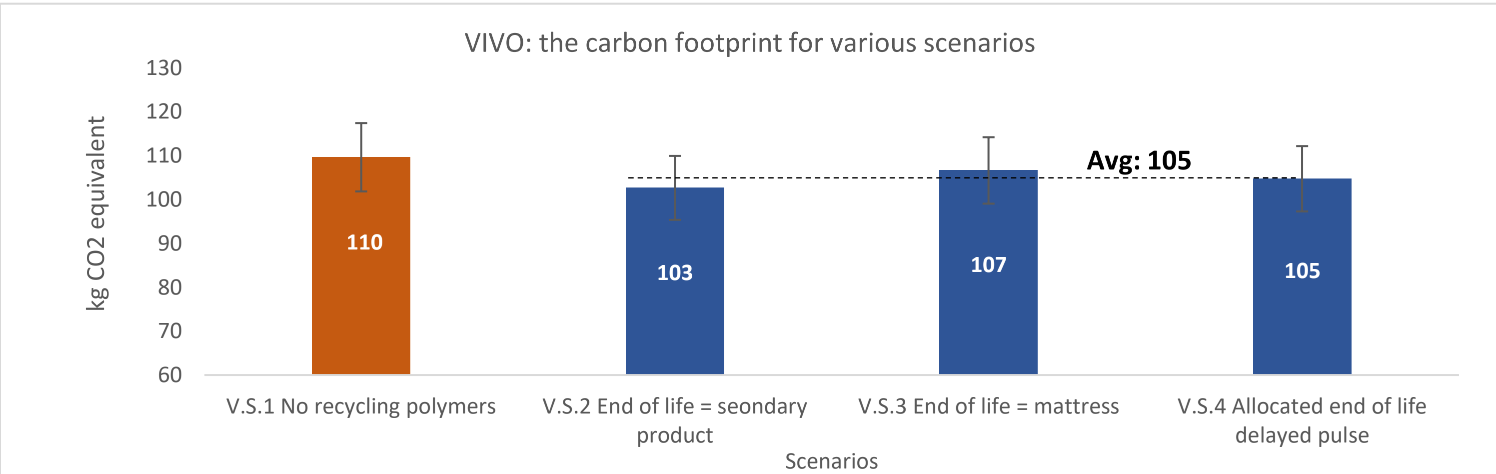


Figure 56. The Carbon footprints for the Vivo allocation scenarios

[19] By polymers, all non-steel materials are meant including viscose and rubbers.

Furthermore, Figure 57 represents the idealized case in which 100% of the disposed mattresses would be collected for recycling. This scenario seems to be far from realistic these days, but can give an indication of the potential of this sort of recycling. All CO2e savings are related to avoided waste incineration.

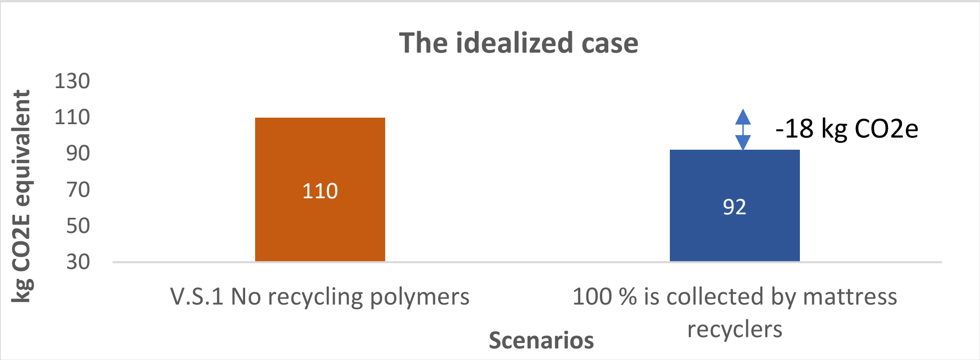


Figure 57. Potential for Open loop recycling (downcycling) for the idealized case (100% recycling)

Conclusions:

- The two realistic scenarios yield more or less the same carbon footprint. The average of these scenarios is 105 kg CO2e, this value will be compared with the evolve in Section 6.4.
- Assuming a collecting ratio[20] of 38% by the mattress downcyclers, at most 7 kg of CO2e reduction is achieved.
- If 100% of the mattresses in the Netherlands would be collected for recycling, then at most a benefit of 18 kg CO2e can be achieved by this type of recycling. This reduction is completely related to avoided waste incineration. 6% of the collected mattresses for recycling, is assumed to be incinerated.
- The carbon footprint of the Vivo can be expected with 95% certainty between the brackets of the error bars. This is more or less 7 percent to both sides (negative and positive). Considering scenario V.S.2 and V.S.3, the carbon footprint is very likely to be between 96 kg CO2e and 114 kg CO2e.

[20] By collecting ratio, the number of mattresses collected for recycling, against the total number of disposed mattress in The Netherlands is meant.

6.4 Part 3: The life cycle of mattresses compared

The ultimate goal of this thesis is to define the environmental performance of the circular mattress Evolve. This is done by a comparative LCA, comparing the circular Evolve mattress, with a conventional exemplar, Vivo. In this section, both mattresses are compared. The following aspects are evaluated:

- The material compositions of both mattresses are compared
- The carbon footprint of both mattresses, assuming no recycling of polymers.
- The carbon footprint of the both mattresses compared
- The contribution of each phase to the carbon footprint

6.4.1 The material composition of the mattresses

First, the two mattresses are compared from a material composition perspective. The composition of the two mattresses can be found in Figure 58 and 59 denoted by the "In mattress" bars. Secondly, an estimation of the total amount of material use, including post-industrial material wastes is provided. This concerns all wastes of the supply processes and the manufacturing process at Auping, except losses in the production of raw materials (such as PET pellet production and steel coil production). Both mattresses are packed in an identical plastic bag, made of PE, that is as well provided in these figures.

One of the main differences, in contrast to earlier mattresses of Auping, for the new circular mattress Evolve, is its material composition:
The Evolve is mainly composed of two materials: PET polyester and Steel, see Figure 58. However, the non-woven layers in the Evolve contain a certain amount melting fibre, that may be problematic for recycling. This melting fibre contains mainly PET (80%), and a small amount of non-PET (20%). The effect of melting fibre on recycling is currently being researched.

The Vivo mattress is composed of significantly more materials, such as rubber, PUR foam and viscose. Therefore, the Vivo is not applicable for high quality recycling or closed loop recycling.

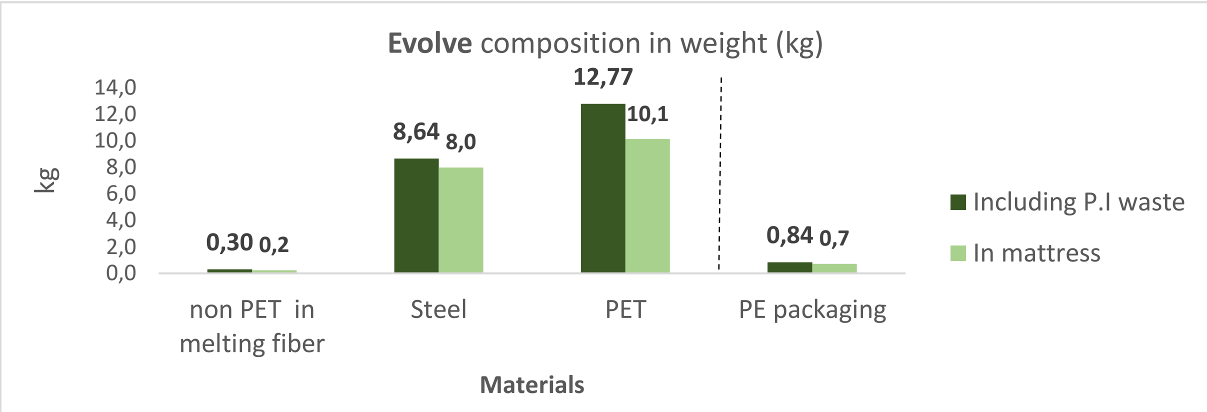


Figure 58. The composition of the Evolve mattress, most right the Packaging is given. An indication for P.I wastes is given as well

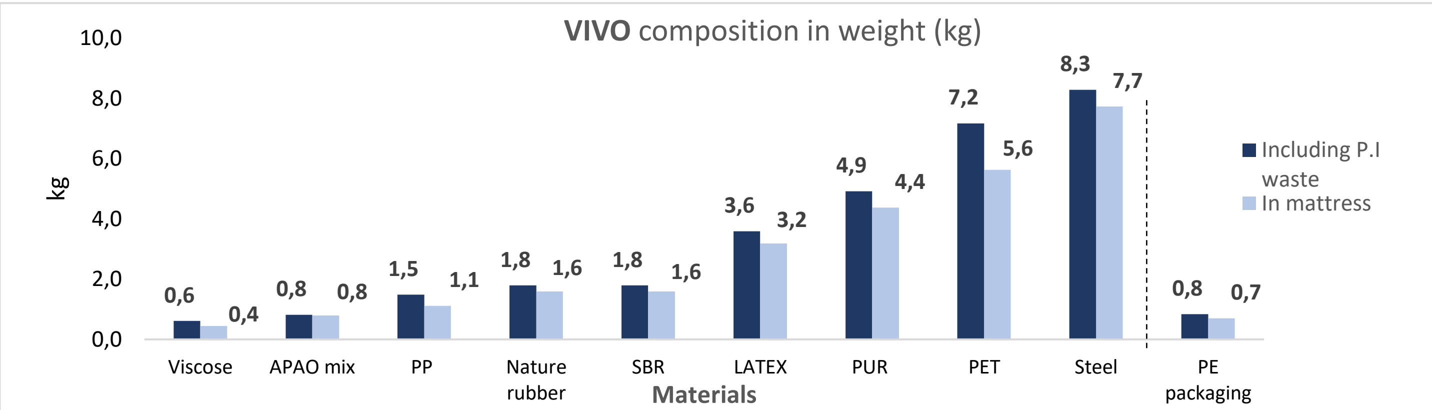


Figure 59. The composition of the Vivo mattress, most right the Packaging is given. An indication for P.I wastes is given as well

Conclusions:

- The Evolve mattress is mainly composed of two materials: Steel and PET. The limited amount of non-pet in the melting-fibre may influence the recycling process.
- The packaging of both mattresses is not engineered to be circular.
- The Vivo mattress is composed of at least nine different materials.

6.4.2 The base scenario, no polymer recycling

If for both mattresses no special recycling process for the polymers is undertaken, the results are given in Figure 60. This can be seen as the start situation, that can be improved by recycling or re-use. Steel recycled credits are still given here, since steel from the incineration residue is as well recycled. For this scenario, the life cycle of the Evolve mattress has an estimated carbon footprint of 92 kg CO2e and the Vivo of 109 kg CO2e.

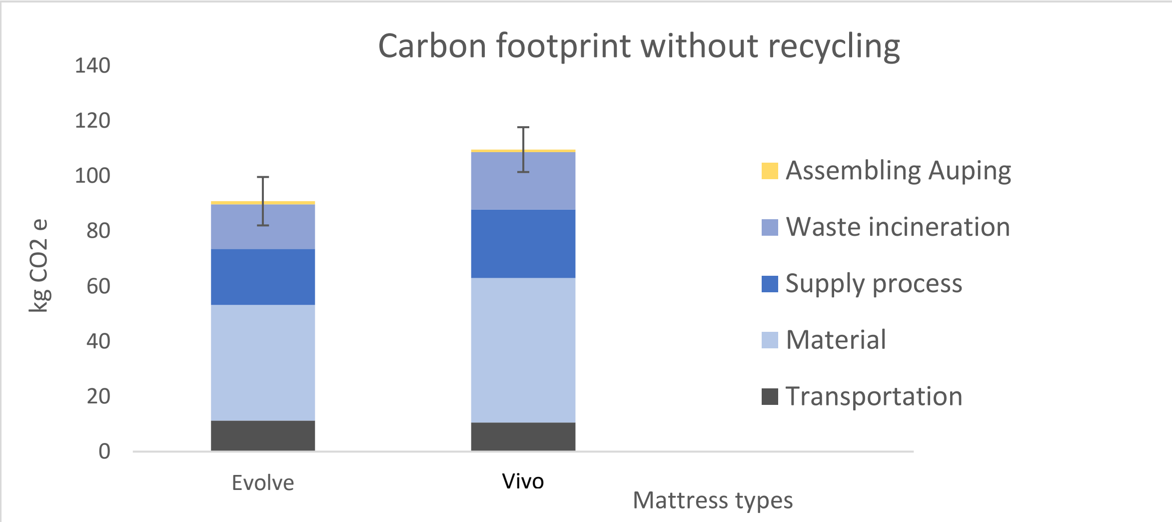


Figure 60. The carbon footprint without recycling of the non-steel materials

Conclusions for the situation without recycling effort:

- The Evolve seems to have a 16 % lower carbon footprint, even if recycling is not taken into account. The error bars have no overlap. Therefore, it can be concluded safely that the Vivo has a higher carbon footprint than the Evolve, if both mattresses are incinerated.
- The raw materials (production and harvesting), contributes most to the carbon footprint for both the Vivo (48%) and Evolve (46%).
- The supply processes and the waste incineration are the second and third largest contributors for both mattress, all between 18% and 23% of the total.
- The assembling process at Auping accounts for only +/- 1% of the total carbon footprint for both life cycles. Hereby, the Evolve is presumed to have a slightly higher carbon footprint for the robotized system.
- Transportation accounts for more or less 10 % of the total carbon footprint in the system.
- If the carbon footprint is determined relative to the mattress' weights, the amount will be more or less equal, both around 4.5 kg CO2e / kg.

6.4.3. Carbon footprint results per scenario.

This is a comparative LCA, intended to benchmark the environmental performance of the circular mattress Evolve. Therefore, for various scenarios, the carbon footprint is given in Figure 61. Scenario V.S.1 and E.S.1, can be used to see the carbon footprint benefits of recycling, but are no realistic scenarios. The error bars represent an estimate of the 95 % confidence interval of the error. The following assumptions are made hereby:

- For the Vivo, 38% of the collected mattresses are brought to a recycler. From this flow, 6% is incinerated and 94% in some manner recycled. The remainder (62%) is assumed to be incinerated without interference of the mattress recycling company.
- For the Evolve, a recycling rate of 89% is assumed for PET for all scenarios with recycling.

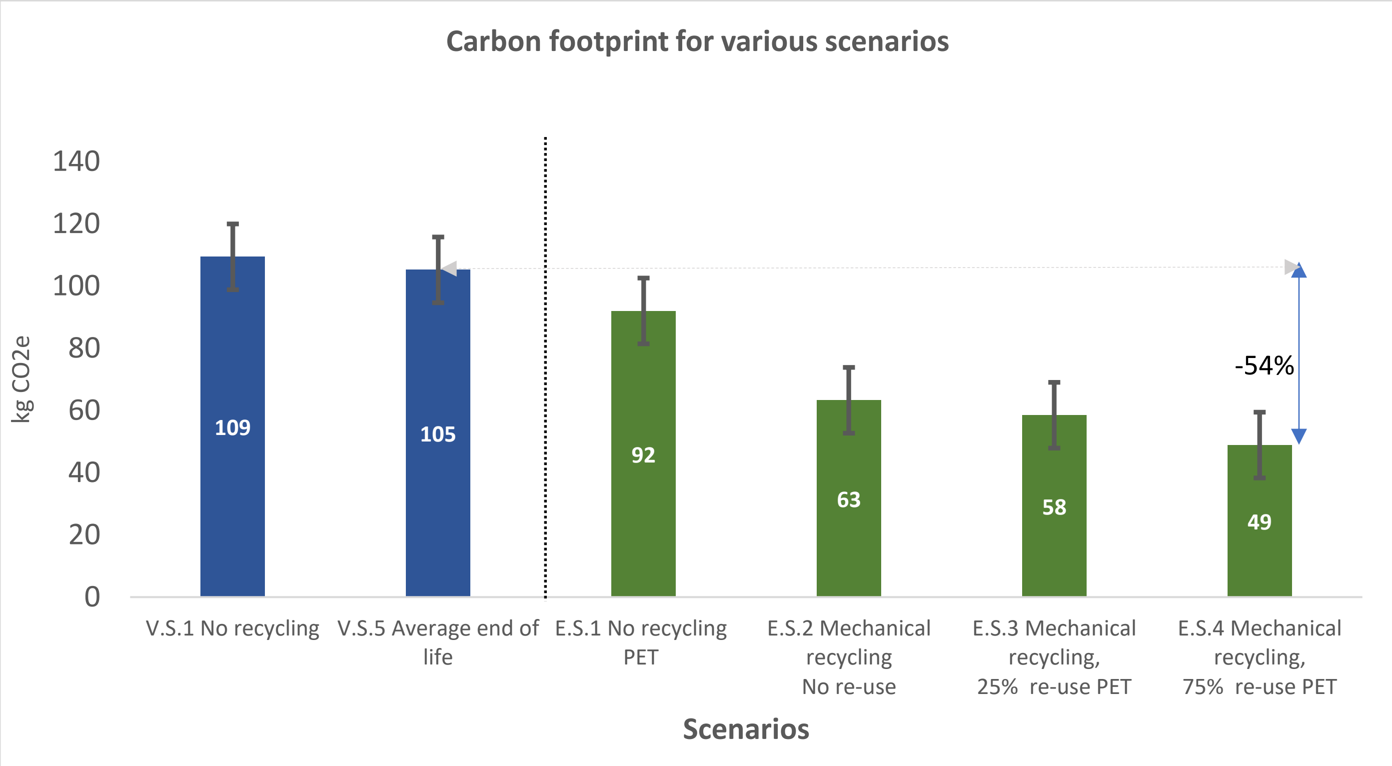


Figure 61. The carbon footprint of the Evolve and Vivo compared for various scenarios. The error bars indicate the 95% conf. interval for mean

Conclusions:

- The Evolve has a smaller carbon footprint for all scenarios.
- If springs are re-used (75%) and the PET is mechanical recycled, the expected carbon footprint is 54% smaller than for the Vivo (in the range between 45% and 60%).
- If for the Evolve the springs and PET are both recycled (no re-use), the expected carbon footprint is 40% smaller than for the Vivo (in the range between 29% and 49%).
- From a global warming perspective, the closed loop recycling of the Evolve is more beneficial, than the current end-of-life process of the Vivo.

6.4.4. Carbon footprint contribution per phase, for recycling

In this section, the carbon contribution of each phase in the life-cycle is given. The transport flow burdens are not directed to one of these phases, but are provided as separate group. The use phase of the mattress is assumed to yield a neglectable small contribution to the carbon footprint. Therefore, this phase is not further evaluated in this study. Two scenarios are highlighted:

- *Life cycle of the Evolve*: with mechanical recycling of PET, recycling of springs.
- *Life cycle of the Vivo*: the recycling process is accounted for secondary product system. *End-of-life = secondary product system for the recycled share (36%).*

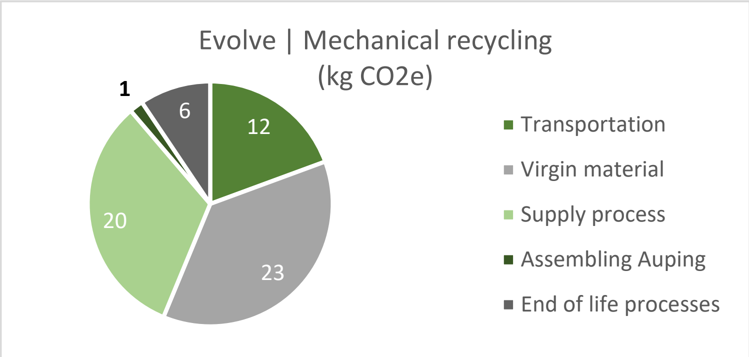


Figure 62. Scenario E.S.2 Mechanical recycling, no re-use

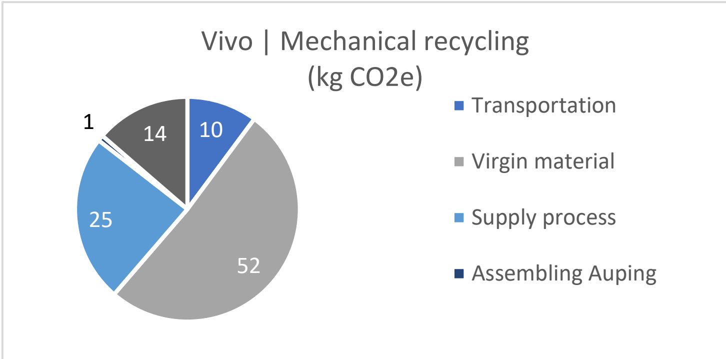


Figure 63. Scenario V.S.3 end-of-life = secondary product system

Conclusions:

- For the Evolve and Vivo the most CO_2e (37% and 51% resp.) is related to the inflow of virgin materials (such as PET Pellets, viscose, PUR and steel coil). By closed loop recycling, the carbon footprint related to virgin material production can be reduced significantly for the Evolve.
- Supply process are the second largest contributors with 24% for Evolve and 33% for the Vivo.
- The end-of-life carbon footprint for Evolve (recycling energy, recycling waste), is significantly smaller than that of the Vivo. This is mainly due to the low recycling rate of the Vivo; most is incinerated.

7. Conclusion and further research

To conclude this thesis, the research questions of Section 1.2. are answered and recommendations for Royal Auping are made. Then, various important limitations of this thesis are discussed. At last, suggestions for further research are given.

7.1 Discussion of research

With the aid of this thesis, the research objective, '*to provide Royal Auping insights in the environmental impact of the Evolve mattress by evaluating its complete life cycle*', is reached.

By answering the three sub research questions that were defined in Section 1.3, the main research objective is achieved:

"Quantify the environmental impact of the circular mattress Evolve, by use of a relevant and reliable tool"

Below, for each of the sub questions the conclusion are described.

Sub question 1: ***"Which of the existing environmental impact methodologies is the best fit to quantify the impact of Auping's new circular mattress?***

After the evaluation of various environmental impact methodologies, the decision is made to analyse the global warming potential by a Life Cycle Analysis (LCA). As a result, for both mattresses the carbon footprint is defined. This decision is made for the following reasons:

- There are comprehensive ISO series for LCAs, that help to model the complex environmental system in a consistent and effective manner.
- Global warming is an urgent issue, the global temperature is increasing at extreme rates, with disastrous ecological and economic consequences.
- Carbon footprinting is a widely used and well known indicator for environmental burden.
- Since 2018, there is a new standard, ISO 14067, that offers guidance and consistency for carbon footprint studies.

Hereby, the first question is answered.

Sub question 2: ***"What information is needed to quantify the life cycle impact of the mattresses"?***

Research question 2 relates to the data gathering process, both content as execution wise.

To acquire the carbon footprints by the selected methodology, emission data for all relevant life cycle processes are needed. Since these emission values depend on various factors, e.g. the energy uses, material wastes and various transport characteristics, this information needed to be collected.

First, all relevant processes in the life cycles of the mattresses were mapped, guided by the bill of materials and flow charts of the system, so that all data requirements were identified.
By an iterative approach, there was a continuous focus on the most affecting processes; all marginal impacts were cut-off. By this mechanism, processes with high impacts, such as the recycling process (and efficiencies) and the transportation of components, received concentration, while for other processes, such as the Auping's assembly processes, rough estimates gratified.

Then, a hierarchical decision tree was made to ensure that, in line with ISO 14067, the best data available was used. To limit the data need, scoping the life cycle analysis started with goal and boundary setting. Primary data could be collected by consulting suppliers, recycling company visits and internal data. For secondary data, two inventory databases were used, Idematapp2020 and Ecoinvent, as these have a good geographical representativeness for European suppliers. For some parameters, the values could be estimated by a mathematical formulas, approximations and intelligent guesses. Then, in the life cycle impact analysis, all parameters were transformed into the selected impact indicator(s), in this case CO2 equivalents. The complete analysis was organized by a custom made excel based tool, that fungated as transparent database and advanced calculation tool. Lastly, to evaluate the uncertainty of data without statistical data, a semi-quantitative approach has been used, combining Pedigree with a Monte Carlo simulation. As a consequence, for the most important results a rough indication of the uncertainty could be provided.

As a result, all required information is collected to draw conclusions for the third research question.

Sub question 3: ***"If any, what environmental benefits can be expected by the new circular mattress?***

By the selected methodology and the gathered data, insights are gained into the performance of the circular Evolve mattress. Therefore, the following conclusions can be drawn:
The new circular mattress Evolve has a lower impact on global warming, by its smaller carbon footprint. By the closed loop recycling of PET, 27 kg CO2e can be saved. Hereby, 19 kg CO2e is saved on virgin material and 12 kg by prevented waste incineration. Besides, Re-use of the steel spring inner core pays-off; an additional 14 kg CO2e can be saved if three-quarter of the steel springs are re-used. However, recycling is only worthwhile if the benefits outweigh the burdens. Preliminary test results are hereby promising, an estimated 4 kg CO2e is caused by recycling, which is a small burden compared to the benefits. However, if the recycling takes place in Austria instead of Deventer, an extra emission burden of 9 kg CO2e should be accounted for additional transport. All in all, if the Evolve is compared to the conventional mattress Vivo, an emission benefit of 54% is expected, for the combined scenario of recycling in the Netherlands and re-use of springs. From a cost perspective, the estimated costs savings on virgin material are €33,-. If the additional costs for re-use and recycling are known, an estimation of the recycling benefit in terms of money can be made.

7.2 Contribution of the thesis to literature and practice

Literature
This report presents the very first life cycle analysis, in which incineration, recycling and re-use for mattresses are compared. In current literature, there is often mainly focussed at the production burden, whereby a thorough analysing of the end-of-life part of the life cycle is lacking. For the sparse cases in which a post-consumer burden is provided, only a single number is given, without specifying the different contributing factors. Therefore, this LCA can serve as first detailed indication for the recycling benefit and burden for mattresses, for both open and closed loop systems. Besides, in LCA literature, a decent method to calculate the transport burden is lacking, for cases with low density goods and inefficient space occupancy. Therefore, often only a rough indication is given, not considering the occupancy rate of trucks and packaging efficiencies of the goods. As a consequence, the approached impact may be a lower bound for the real transport impact for these cases. In this thesis, new transport formulas are proposed, by which more realistic estimations of the transport impacts may be obtained.

Practical contribution
This thesis yields the first quantitative prove that the circular mattress Evolve, could have a positive contribution to the environment. The effect of recycling, re-use and different transportation alternatives, as approximated in this study, can be used for strategical and tactical decision-making. In fact, based on the intermediate results from this thesis, Auping intensified researching the opportunities for re-use of the mattress springs. Besides, the results from this thesis are used to support the business case internally and externally, and as supportive argument for future investments for recycling machinery. Furthermore, the draft version of this report is shared to a collaborative partner of Auping, that is expertized at LCAs. Based on specific information in this thesis, such as flowcharts, internal and external gathered information and the scenarios, a broader analysis will be done through dedicated LCA software by this party. As a consequence, the regular time intensive process of data gathering and the mapping of flows (within the life cycle), is shortened significantly.

7.3 Limitations

This is the primer study initiated by Auping that evaluates the life cycle of its products. In general, LCAs can be seen as less exact researches, due to the numerous assumptions and limited data availability. The limitations in this section are given in two instances. First, relevant limitations related to the use of data used in the model, the parameter uncertainties, are given:

- The free databases used in this LCA have a limited number of inventory rows. As a consequence, for some processes less adequate data is used to describe the burden.
- Only guidelines were provided to external parties for the gathering of primary data. As a consequence, potential bias or inadequateness cannot be checked. Besides, the majority obtained data lacks an exact description of the data measuring method. In order to enhance the certainty and consistency of the used data, a protocol could be effective. In future research, such a protocol is further discussed.
- The parameters for transportation, such as the packaging volume efficiency and occupancy rate, are based on rather rough estimates. Since these are multiplicative factors, the impact of different rates can be great on the carbon footprint.
- The post industrial waste flows are determined by the processes characteristics, rather than measured by real data. Measurements at the Auping factory and at suppliers could give a more accurate result.
- The recycling emissions are based on preliminary tests and machine specifications. The LCA results can be updated when better information becomes available.

Furthermore, there are also limitations related to the modelling decisions: the scenario uncertainties. These decisions should be taken into account for the interpretation of the results. Therefore, in the light of the LCA outcomes, the following limitations should be considered:

- Material depletion is not taken into account in this LCA. Especially for closed loop recycling, this is an important factor to consider.
- The presented carbon footprint savings assume a non-limiting inflow of secondary material for recycling. However, during the first years of the Evolve, the sales amounts are likely to exceed the number of mattresses disposed. For this scenario, more virgin material is required for production, as there is not sufficient granulate available. Therefore, a higher carbon footprint can be expected for the first period after the release.
- The Evolve already has a 15% lower carbon footprint, if both the Evolve and Vivo are fully incinerated. This can likely be explained by the weights; the Vivo is 19% heavier.

7.4 Recommendation and future research

7.4.1 Recommendations for Auping

In line with Auping ambition to become a circular company in 2030, Auping has a need for a quantitative tool to measure its environmental performance. Therefore, this LCA yields the first thorough impact analysis of one of its product over its complete lifecycle. Through the new insights of this thesis, We make the following recommendations to Auping:

1. We recommend Auping to invest in a complete, efficient and generally accepted tool to measure impact. In a commercial organization, the cost-benefit of an activity plays a dominant role. As a consequence, it is unlikely that a similar time-investment can be made for all Aupings products, as have been done in this thesis. However, the use of dedicated software can improve the (time)-efficiency, consistency and transparency of LCA analysis. Still, time should be invested to acquire software specific skills. In this light, the tool SimaPro is recommended, as this is a relative comprehensive tool, that is already being used by a partner organization (knowledge sharing). To use this specific software, a licence for an inventory database is required as well. We suggest to use Ecoinvent, as this holds the greatest amount of geographically representative data for Auping and it is a widely accepted source.

2. In case the management of Auping decides not to invest in Life cycle Analyses, We advise to invest in a 'tool' that enhances the material flow knowledge. The goal of such a tool could be twofold:
    1. To enlarge the knowledge of the recyclability of materials.
    2. To get a complete overview of all material flows in the life cycle of products.

    By inventorying these materials flows in the life cycle of products, the following advantages can be achieved:
    - ***Material wastes can be reduced more effectively***, when its occurrence is known.
    - ***The secondary raw material quality can be guaranteed,*** for a high level of material flow control throughout the life cycle. Product upgrades can involve a change in material composition and recyclability. These and other changes should be monitored accurately, to avoid a quality loss at recycling.
    - ***The recycling logistics can be organized more efficiency*** if there is a good overview of the different material flows (old material, secondary granulate). The companies that use the secondary granulate for component production are likely in need of what and how much they can expect.
    - ***The material passport can be enhanced by more reliable data.*** Information such as, the amount of recycled content in the product, the age of the pocket-springs (in case of re-use) and the exact composition of the product.

    In addition, compared with a LCA this material flow 'tool' can have another practical advantage: Measurement of material flows are in general straightforward; These can be weight or measured. Energy flows, toxicity and other environmental impacts can be significantly more challenging to quantify adequately.

7.4.2. Future research

As mentioned in the introduction of this thesis, the information in literature about closed loop recycling, especially for mattresses, is scares. As a consequence, this the first openly available LCA that compares a mattress with closed loop recycling, with a conventional, linear exemplar. Therefore, there are numerous grounds for further research, from which a selection is given here. These grounds can be divided into two categories: Those related to the validation and further improvement of the current study and future studies, and relevant adjacent paths to further investigate.

In order to further improve the current LCA and future studies, the following aspects could be investigated:

- *The evaluation of an industry specific protocol for primary data gathering.*
  An inventory data gathering protocol may help improve the consistency and reliability of the Life cycle analysis. This protocol should explicitly instruct on how, when, where, and how frequent primary data should be collected. Ideally, such a protocol is industry specific, as for very different processes identical measurement guidelines may be ineffective. E.g. for measurements at a nuclear plant, a different protocol will be effective than for a fabric producer. In current literature, there is no such a protocol yet for the mattress industry.
- *Validation of the background/ foreground ratio of standard data*
  The main or foreground processes (such as spinning and calendaring) are assumed to comprise most of the relevant process emissions. It can be worthwhile to validate this assumption for the textile industry.

Furthermore the following aspects can be relevant to study as extension to the current work:

- *Analysing the effect of closed loop recycling, to resource depletion*
  For practical reasons, this LCA is only focused on global warming. However, resource depletion strongly relates to closed loop recycling as well, as direct reflection of the virgin material consumption.
- *Development of a secondary material sharing platform*
  Closed loop recycling systems are in many cases less efficient individual companies. Industrial symbiosis is a concept in which companies exchange wastes and by-products, in order to minimize waste and maximize costs. It would be interesting to investigate the possibilities for mutual sharing of e.g. PET waste flows between companies, to improve the efficiency and effectiveness of its recycling systems. For example: If old PET bottles can be used to produce mattresses and vice versa, investments and operational costs of machinery can possibly be reduced.
- *Researching the potential of re-use of materials in a mattress industry*
  Re-use is the most sustainable form of waste management. Therefore it would be interesting to investigate how and with what the potential benefits and implications, re-use can be implemented in the luxury segment of a market.
- *Investigation of the chemical recycling potential*
  Chemical recycling has developed over the recent years and might be applicable on an industrial scale in the near future. It would be interesting to compare the (test) results and environmental impacts of this type of recycling to mechanical recycling.
- *Researching impact reduction possibilities related to transportation*
  The contribution of transportation to the total environmental impact could be improved by the smart aggregation of truck loads. After the supply of components to the factory, trucks often back mostly empty. The same yields for the transportation of new and old mattresses. By the use of a collaborative planning model, the vehicle occupancy rates can be improved, resulting in potential cost and environmental benefits for all involved parties (Schulte et al., 2017). Besides, various operation research techniques can be used to further improve the transportation efficiency, from an environmental point of view. A selection of relevant optimization methods for sustainable transportation is given in (Armas et al., 2019)

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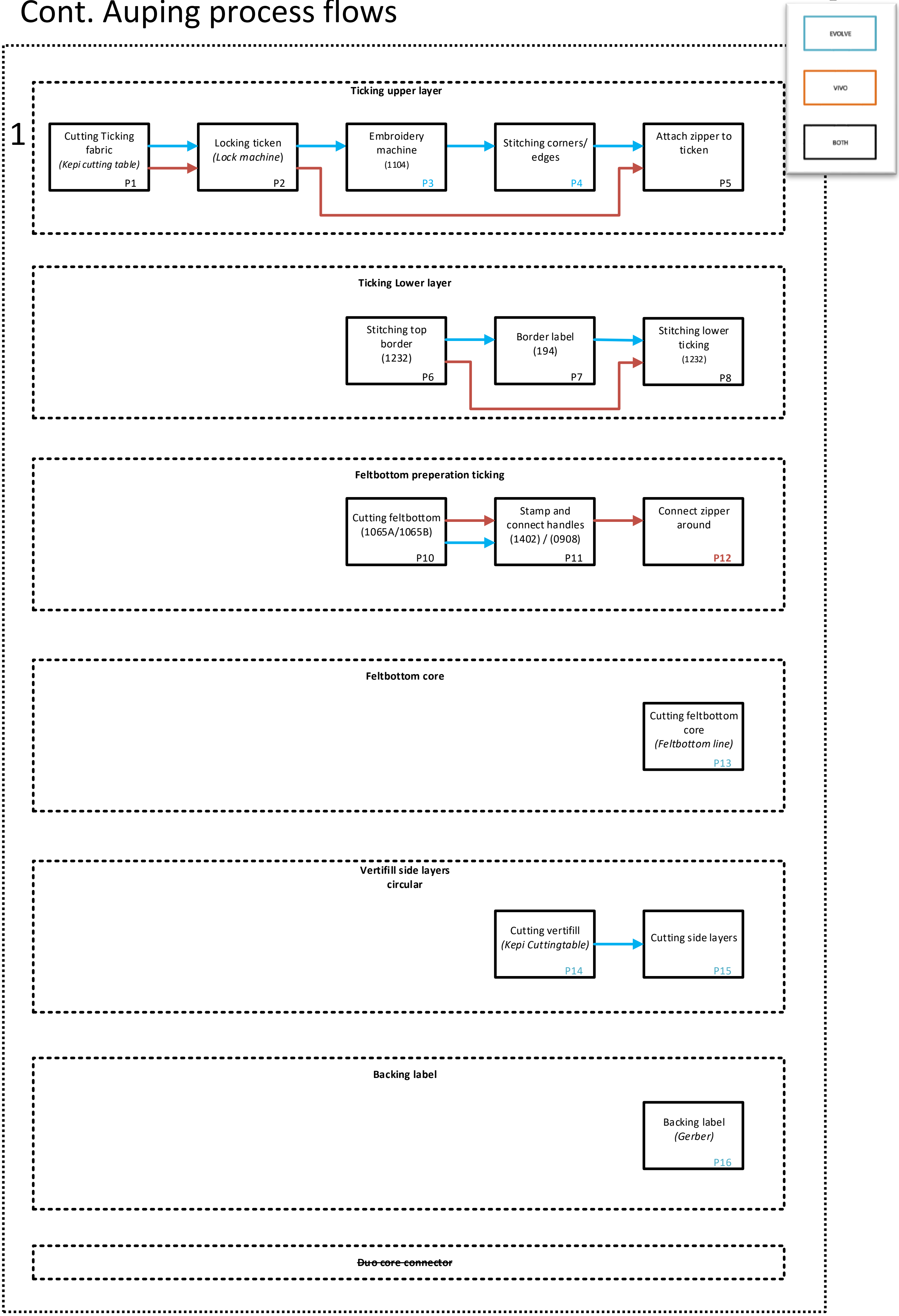
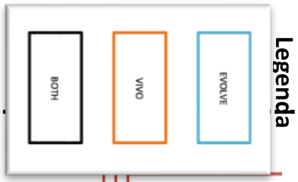
Cont. Auping process flows



Cont. Auping process flows



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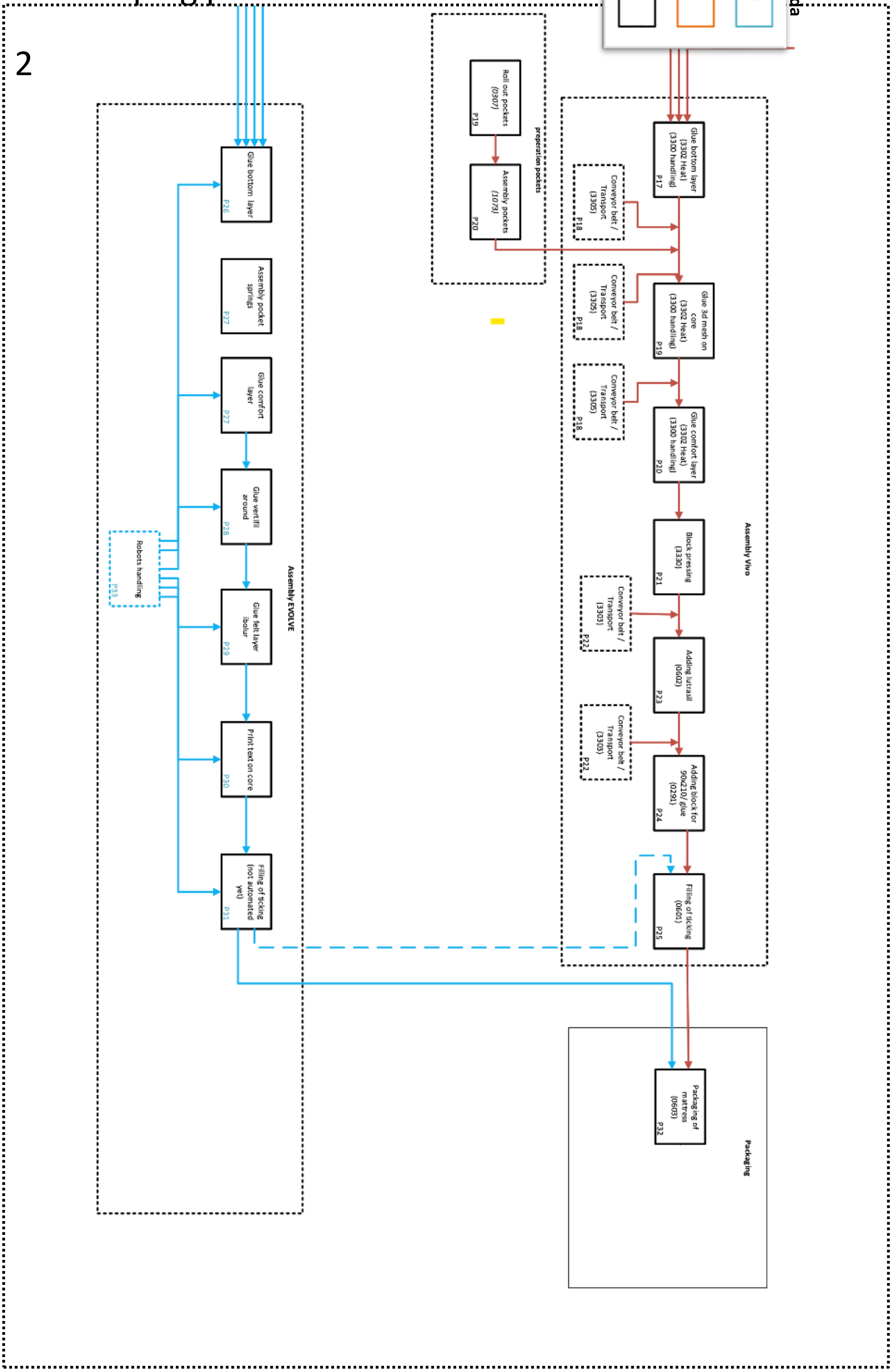


Appendix 3 Eco-costs

Another expression to indicate the impact of products or processes are eco-costs. Eco-costs are a measure to quantify the environmental burden, based on the estimation of prevention costs. The eco cost is an aggregated indicator for effects of various factors e.g.: human health, ecosystems, resource depletion, that represents the compensation costs. In contrast to most alternative indicators (e.g.. carbon foot printing), that are damage-based indicators. In other words, eco-costs represent the amount of invested money (in €) needed to reduce the material depletion and pollution effects, in line with the earths carrying capacity (Vögtlander 2017). One example related to the carbon footprint for the eco-costs 2017 system version 1.6 is:

For each 1000 kg CO2e emissions, €116,- shall be invested in off-shore windmill parks (and other greenhouse reduction systems at that price or less).

Thus, the eco-cost for carbon footprint are assumed to be 0.116 €/kg CO2e equivalent. These calculations can also be made for other environmental impacts as fossil resources, acidification, terrestrial ecotoxicity, marine ecotoxicity, and human toxicity (e.g., summer smog, fine dust). The eco-cost methodology is planned to be updated every 5 years, according to the most recent insights and developments.

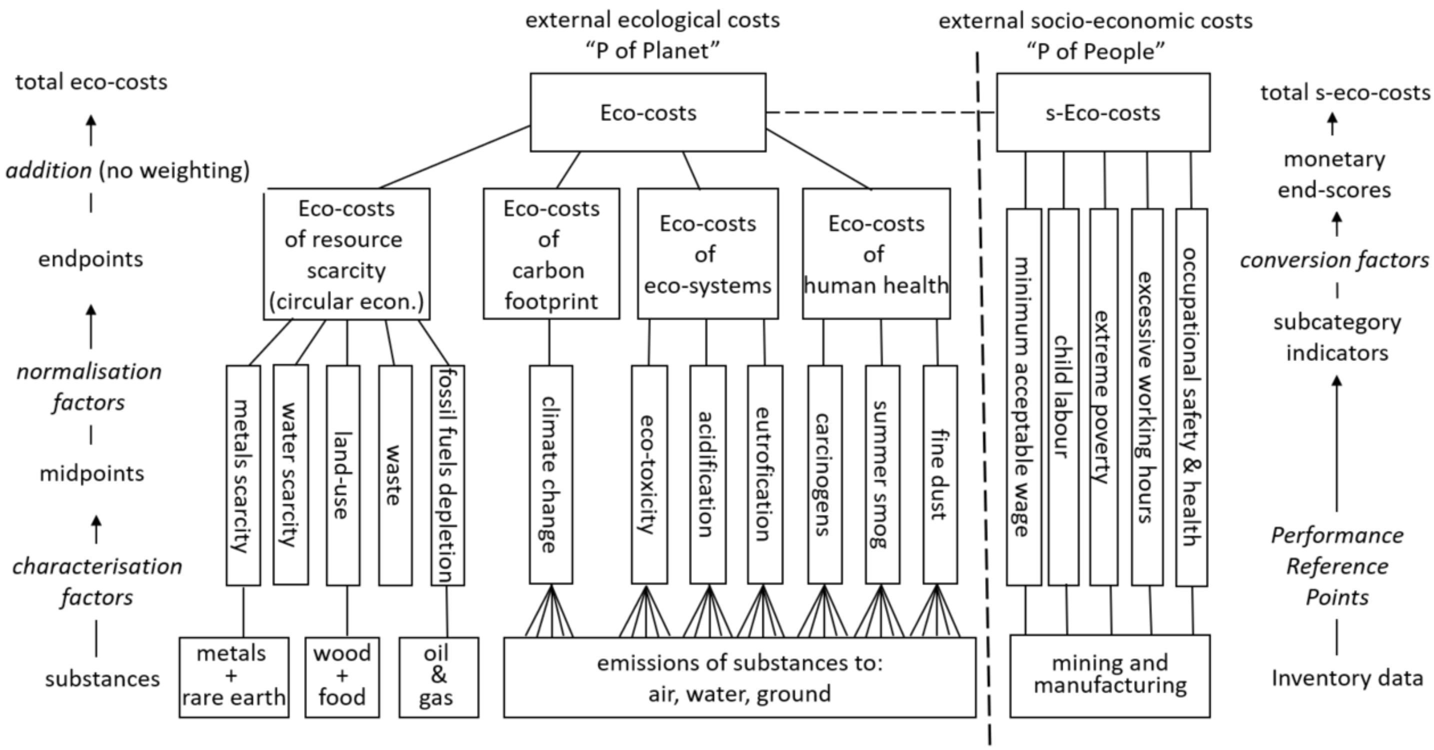


Figure 64. Schematic representation of the eco-costs 2017 model

Advantages of the eco-costs system are (Vögtlander 2017):

1. The calculations are relatively simple and transparent
2. Material depletion is considered, relevant for cradle to cradle calculations.
3. It is expressed in a standardized monetary value, the euro. Which appears to be easily understandable by instinct.

However, the concept of eco-costs is less widespread yet on all levels of the society, compared to e.g. carbon foot printing. Communication of environmental impacts in terms of carbon footprint, could be an advantage for direct B2B communications.

Eco-costs factors

For emissions of toxic substances, the calculation factors of Table 32 are recommended to determine the contribution to the eco-costs. In the column midpoint table, the recommend midpoint tables are listed.

Category	Multiplier (marginal prevention costs)	Midpoint table
acidification	8.75 €/kg SOx equivalent	ILCD 2011 Midpoint
eutrophication	4.17 €/kg phosphate equivalent	CML-IA baseline
ecotoxicity	340.0 €/kg Cu equivalent	UseTox 2
human toxicity	3754 €/kg Benzo(a)pyrene equivalent	UseTox 2
summer smog (respiratory diseases)	6.0 €/kg NOx equivalent	LOTOS-EUROS model
eco-costs of fine dust	35.0 €/kg fine dust PM2.5 equivalent	UNEP/CETAC plus ILCD 2011 Midpoint+
eco-costs of global warming	0.116 €/kg CO2E equivalent	IPPC 2013, 100 years

Table 32. The eco cost factors

The following midpoint tables, which are used in the eco-costs 2017 system version 1.6, are recommended to use by the International Reference Life Cycle Data System, ILCD:

- eco-costs of abiotic scarcity (metals, including rare earth, and energy carriers)
- eco-costs of land-use change (based on loss of biodiversity, e.g. used for eco-costs of tropical hardwood)
- eco-costs of water (based on the Baseline Water Stress indicator - BWS - of countries)
- eco-costs of landfill

Appendix 4 Suggested criteria for hierarchical decision method

If Auping decides to apply a multicriteria decision tool for the evaluation of environmental impact indicators, this section might be helpful. The full methodology of AHP and WSM is out of scope of this thesis. However, independent of the methodology Auping is going to use to scope their environmental strategy, certain criteria will be used to define their strategy. Suggestion for these criteria are given below:

- **Product group relevance:** The estimated relevance of this impact category for the product group mattress. One example:
  E.g.: the midpoint category mineral resources is not a first focus point, as there are no (or very limited) scarce metals involved in the life cycle of both mattresses.

- **Industry relevance:** Is it acceptable for the industry politics to include or exclude this impact category. Such as:
  Considering the upcoming Extended production responsibility, what factors should be mapped?

- **Operational/tactical relevance:** Does the impact factor contribute to the current and future needs of the manufacturer:
  - *E.g. the selection of suppliers can be adapted by the knowledge of that impact indicator*

- **Communicational/commercial potential**: Can the indicator be relevant for communicational or commercial purposes?
  - *Are the results easy interpretable by potential stakeholders? Is the impact category a widely recognized standard?*

- **Practical feasibility:** Is it practically feasible to obtain the specific impact indicator?
  Is the relevant information likely to be sufficiently available? Is a good quality result for this impact category realistic within the timespan of this study?

Appendix 5 Brief evaluation of impact indicators

Based on an evaluation of the involved student, a selection of points are addressed below. However, these are no statements or opinions of Auping, but only based on the student's brief evaluation.

The following conclusions are drawn:

- The **human safety** (and toxicity) is the highest priority of the manufacturer (Auping, 2020), which translates to intensive external and internal testing of products and processes and careful decision making on quality and health aspects. For all materials in the Evolve mattress, various researches have yet been done on human toxicity. For these reasons, the direct focus on human toxicity is assumed to be of lesser direct value for either tactical, operational or communicational purposes at this point in time. However, as mattresses are being used daily with intensive physical contact, human toxicity is a continuous attention point.
- **Global warming** is a broadly recognized worldwide problem. According to a report of (EPA 2018), a large share of the global warming impact can be related to the material extraction and early processing of products. As indicator of global warming, the carbon footprint is often used. The fact that over a million mattresses are disposed yearly in the Netherlands, without a significant recovery of the energy value of the material, reveals the relevance of a carbon footprint study.
- In general, for the textile industry, **water consumption** is an important factor to consider. For clothes, significant amounts of water are required during the production phase (dying, washing) and the use phase (washing). Especially for cotton, the harvesting and processing steps in the production phase, account for a large amount of water (Chapagain et al., 2005). The materials used in the mattress see Section 23, are less water intensive in comparison with cotton (1 kg cotton = 22000 L, 1 kg viscose 640 L, 1 kg polyester = 62 kg) (Chapagain et al., 2005).
- All fabrics, foams and adhesives are produced in the EU. For this region, industrial water discharge is under strict regulations. For these processes, ecotoxicity of water is less likely to be a critical issue. However, the majority of synthetic polymer production takes place in Asia, where discharge of chemicals in freshwater is still an environmental issue. As the exact whereabouts of the raw materials is not known yet, **freshwater ecotoxicity** may be a relevant point to consider.
- **Fossil fuel depletion** is assumed to be an important factor to consider for oil based plastics. Besides, the production processes that use fossil fuels and transportation account for fossil fuel uses.
- Using endpoints simplifies the interpretation of the results (e.g. "*Alternative x is better for the ecosystem, then y")*, but increases the uncertainty of the results. (RIVM 2018). In conclusion, obtaining a good quality result for an endpoint indicator may be both data and time intensive.

Appendix 6 Assumptions for inventory data

Material inflow

For the material inflows of the Evolve, the following assumptions are made:

- The carbon footprint of PET polyester and bico polyester are assumed to be more or less similar (bico polyester may have a slightly higher carbon footprint per kg material, as the efficiency of the production process is less crystallized). (DSM, 2020). The amount of non-PET in these layers is assumed to be 4% of the total weight. The difference in carbon footprint for this alternative material is assumed to be significantly below the 5% lower bound. Therefore, for all parts that contain a mix of PET polyester and melting fibre, the material burden is taken as if it is 100 percent PET polyester.
- The steel used for the pocked springs is assumed to be most similar in characteristics and composition with the *Idematapp2020 50CrV4* spring steel. Therefore, this data point is used to model the steel inflow. See Appendix 7 for complete reasoning.
- The felt layer of VEBE, is assumed to be composed of a higher grade polyester, most comparable with bottle grade polyester.

For the material inflows of the VIVO, the following assumptions are made:

- The carbon footprint of PET polyester and bico polyester are assumed to be more or less similar (bico polyester may have a slightly higher carbon footprint per kg material, as the efficiency of the production process is less crystallized). The amount of non-PET in these layers is assumed to be 4% of the total weight. The difference in carbon footprint for this alternative material is assumed to be significantly below the 5% lower bound. Therefore, for all parts that contain a mix of PET polyester and melting fibre, the material burden is taken as if it is 100 percent PET polyester.
- The steel used for the springs is most similar in characteristics and composition with the *Idematapp2020 50CrV4* spring steel. Therefore, this data point is used to model the steel inflow. See Appendix 7 for complete reasoning.
- The exact composition of the VIVO adhesive is not known. Therefore, an estimate is made based on information received from its supplier. See Appendix 8 for complete reasoning.
- The inventory data point "*film LDPE 50 mu" deviates in thi*ckness, from the actual packaging (that is 75 mu). Presumably, the production of thinner foil involves more energy per kg output compared to thinner foil, as more pressure is required to obtain the right size. Therefore, the data point *LDPE 50 mu*, can be seen as upper bound for energy usage. However, the packaging foil used for both mattresses is identical. Therefore, for both mattresses *Idematapp2020 film LDPE 50 mu,* is used.

Supply processes

For the supply processes in general, the following assumptions are made:

- All in-between energy for transports (e.g. conveyor belt, forklift) is assumed to be considerably small in comparison with the main processes. These transports are therefore cut off. (<5 % lower bound, so cut-off)
- The secondary data is assumed to capture background processes to a reasonable extent. In future research this assumption can be validated.
- In the used secondary databases, no row corresponds well with the spring production process. Deep drawing is assumed to be most close to this process and is used for both mattresses. This does not influence the comparison significantly as for both mattresses the amount of springs is more or less equal.
- For steel spring production the extra steps such as cooling and checking are assumed not to contribute significantly to the total energy burden.
- The knitting process energies are related to the thickness of the yarns. New datapoints are generated by interpolation for the thicknesses in the fabrics of the mattress. See Appendix 9.
- The required energy for Vivo hotmelt production is mainly set by the heat for the mixing process. (Adhesive company X 2020). The other processes are therefore cut-off.

The steel used in the pocket springs are produced by a steel drawing/ extrusion process.

Appendix 7 Spring steel dim EN 10270-1

The four steels listed in the Idemat2020 database are evaluated for the best match with "Dim EN 10270-1", the steel used in the mattresses. The green marked values denote the matches with the spring steel in the mattresses. The production method (in the description row) is assumed to be the most important factor to represent the steel. The listed steel, 50CrV4, is the only steel that is "cold drawn", the production technique for the steel used in the mattress.

For these reasons, 50CrV4 spring steel seems the best match and is therefore chosen to represent the steel material inflow, for Evolve and Vivo. Data is obtained from, (Virgamet sd)

Spring steel declaration	**Dim EN 10270-1**	*Unit*	**38Si6**		**50CrV4**		**55Si7**		**67SiCr5**	
description steel	cold drawn unalloyed spring steel		Cold rolled narrow steel strip for heat treatment		Cold drawn or turned and soft annealed		cold rolled and hardened		cold rolled and soft annealed	
Density ρ	7.85	*g/cm^3*	7.7-8.03		7.83		7.8		7.83 g/cm^3 at 20 °C	
Elastic modulus E	206	*GPa*	190-210		217 GPa		217 Gpa		217 GPa	
Poisson's ratio ν	0.29	*[-]*	0.27-0.30		0.29		78		0.28	
Reduction of area Z	28 - 40 %	*30%*	0.53		0.40-0.50					
Shear modulus G	81.5	*GPa*					650		78	
Tensile strength Rm	1020 - 2650	*Mpa*	1180～1370		0					
Coefficient of thermal expansion α	1.32E-5	*1/K*			1.05E-5				10.5	
Max service temperature Tmax	500	*°C*	500							
Melting point Tm	1289 - 1478	*°C*	1370-1400		1370 - 1425 °C					
Electrical resistivity ρel	1.43E-7 - 1.74E-7	*Ω·m*	0.7		2.31E-7		2.50E-07		0.23	
Composition (in percentages)	≥	≤	≥	≤	≥	≤	≥	≤	≥	≤
Mn	0.4	1,20	0.5	0.8	0.7	1,1	0.7	1	0.4	0.6
C	0.35	1,20	0.35	0.42	0.47	0,55	0.52	0.6	0.62	0.72
Cu	0.2		0		0				0	
Si	0.1	0,14	1.4	1.6	0.35	0,4	1.5	1.8	1.2	1.4
P	0.04		0	0.05	0.038	0,04	0	0.05	0	0.04
S	0.04		0	0.05	0.02	0,03		0.05	0	0.04

Table 33. Steel evaluation sheet. Various steel types from the Idematapp2020 database are compared with the spring steel in the mattresses

Appendix 8 APAO adhesive production.

For the assembling of the Vivo mattress, an APAO adhesive is used. The exact composition of APAO adhesive is sensitive company data and could not be retrieved. Different compositions are used in mattresses, e.g. based on polyolefin, thermoplastic rubber, resin or ethylene vinyl acetate (Deliege 1995)

In general, there are three forms of APAO adhesive (hotmelt.com 2020):

- Homopolymers: made of 100% propylene
- Copolymers: a combination of polypropylene and either Ethylene or Butene-1
- Formulated: Very specific combination of materials. A mix of the ingredients of homopolymers and copolymers, with a specifically selected resin depending on the application. According to the information of the supplier, the adhesive is a mix of APAO and a C5 resin.

Three types of C-resins are (Eastman chemical company 2020):

1. Epoxy resin: c2 resin
2. Melamine resin:. Melamine formaldehyde is mainly used in plastic laminate and overlay materials.
3. Phenol formaldehyde "(PF) resin is widely used as coating, adhesive, and foam material due to its many advantages, such as the good mechanical and electrical insulation property, durability, and heat and flame resistance, producing low amounts of smoke during burning".

The latter is the most likely candidate, as mattresses are composed of foam material layers. According to the adhesive supplier, the mix consist of 60% APAO and 40% resin. Therefore, the adhesive is modelled [21]by the following two inventory rows:

- 40% *Idematapp2020 PF (resin)*
- 60% *Idematapp2020 Propylene*

[21] The percentages are based on the weights

Appendix 9 Textile and non-woven processes

For both mattresses, most of the components are either polymer fabrics or foams.

The foam layers are made by a batch process: two or more materials are put in a bath. Thereafter, a chemical reaction takes place that make the materials foam. Then, after cooling, a block of foam is obtained. The latex layers are obtained by a vulcanization process. Hereby, synthetic SBR rubber is mixed with natural rubber. For the remainder, all non-foam layers, are first spun, processed mechanically processes (knitting) or bonded by the combination of heat and pressure (thermoforming, calendaring). See Figure 65.

The energy consumption of these processes vary for different types of materials and the desired textile characteristics as yarn thickness and the density of the fabric. According to (Natascha M. van der Velden & Martin K. Patel 2014), the LCAs of textile products can only be accurate when yarn thickness is considered. Spinning thinner yarns is in general more energy consuming, compared to thicker yarns (Muthu 2015). A measure often used to specify the thickness of the yarn is the decitex or dtex, that is equal to 1 gram per 10.000 meter. At spinning, a yarn of a certain thickness is made from the inflow material (e.g. PET pellets or viscose fibres). In standard data-bases for spinning, weaving and knitting, sometimes an indication of the dtex is given, such as:

- *Knitting 300 dtex. (Idematapp2020)*

This data point represents the knitting of yarns of 300 dtex. For cotton, the research by (Natascha M. van der Velden & Martin K. Patel 2014), provided extensive dtex specific data for spinning, knitting and weaving. However, for synthetic polymers and viscose, less specific inventory data is available.

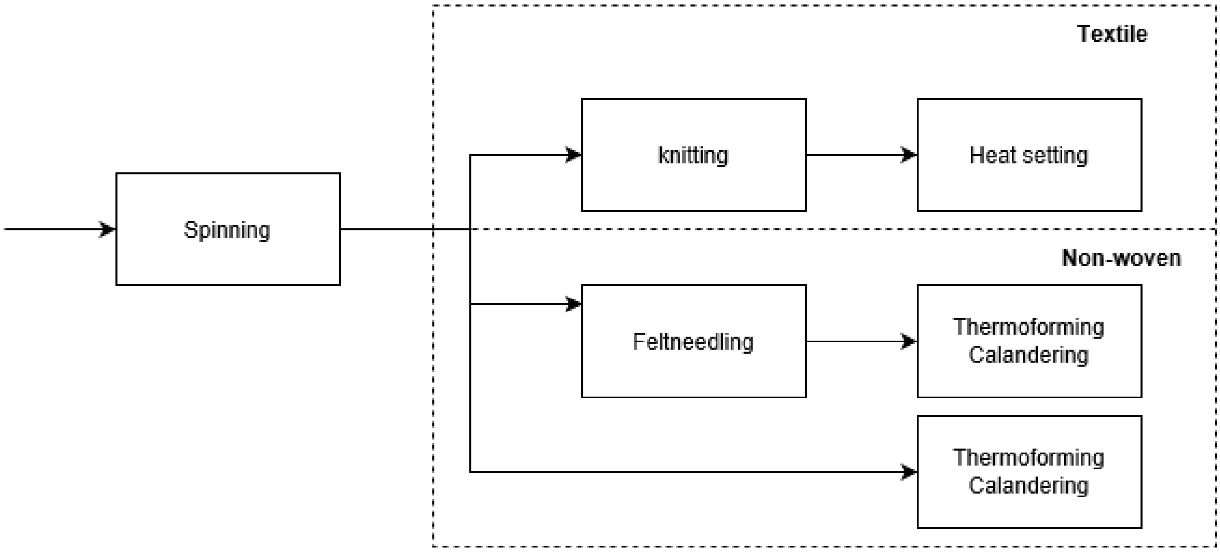


Figure 65. For most of the textile and non-woven layers the production processes

Knitting

The data points of knitting in the *Idemat 2020* database, assume a proportional relation between the energy and dtex (van der Velden et al., 2014). Therefore, for knitted fabrics that differ significantly from the available standard data, an estimation can be done based on the distribution in Figure 66. As a consequence, for the estimation of some of the 3d mesh knittings, the value assigned with the triangle can be used to represent these layers with this specific thickness (650 dtex). However, in this LCA, there is decided to choose the conservative side, and select the closest inventory data row from the standard database. The effect of this decision is very limited in this LCA (<1 kg CO2e difference in total).

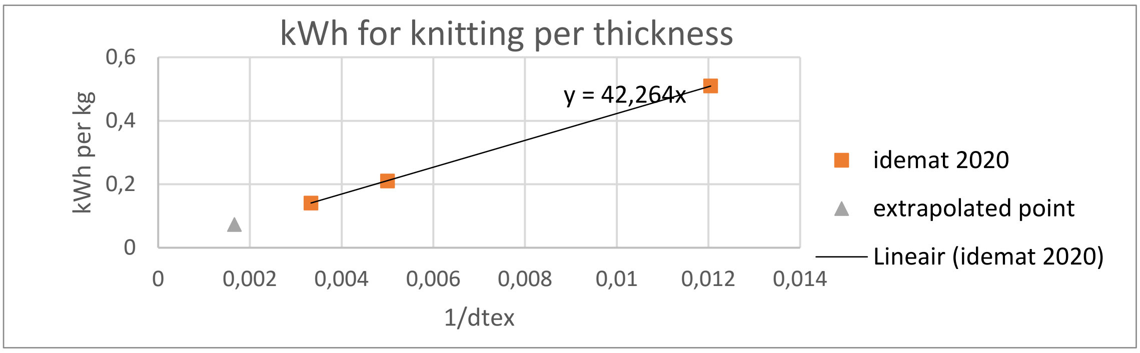


Figure 66. The relation between the dtex and the energe consumption for knitting

Generic data compared with data from suppliers

A textile company expertized in knitting fabrics in Western Europe, provided an estimation of the energy use for knitting, washing and heat setting of polyester. This data can be found in Table 28. Figure 66 shows the data points for knitting from the Idemat database per dtex and the site specific data point from textile company x, plotted against a linear distribution. The knitting data and data point from textile company x, seem to be captured reasonably well by a linear distribution. The deviation from this distribution is 5% percent.

Textile company x	*1 running meter*	*Run meter =2,4 m2*
Knitting	0,3	*kWh/ running meter*
Washing	0,14	*m3 gas/ running meter*
Drying/ heat setting	0,12	*m3 gas/ running meter*

Table 34. Data provided by textile company x, for it's knitting, washing and drying process of a polyester fabric of approx. 120 dtex

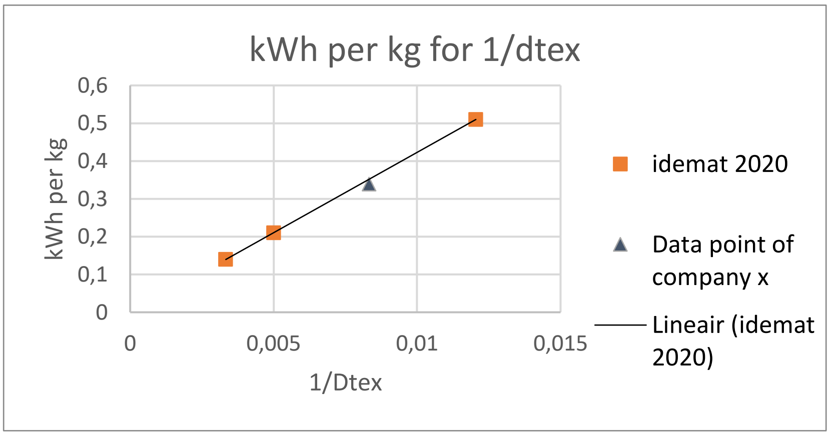


Figure 67. The energy needed for knitting. The orange dots represent the data form the Idemat 2020 database. The blue triangle represents the energy use estimation of textile company x.

Appendix 10 An indication for chemical recycling

The upcycling credits *Idematapp2020* can be used as indication of the CO2e spared on virgin materials, by chemical recycling. This value should only be interpreted as rough estimation, as this is a generic value and the technology is still in an early phase of development. For a more accurate approximation, first the recycling rate for the specific material mix should be known. In Table 35, the expected savings for this type of recycling are provided. Compared to the Mechanical recycling scenario of the Evolve in section 6.2, 58% less CO2e is spared on "virgin material". Thus, chemical recycling seems less efficient than closed loop mechanical recycling.

Chemical recycling: P. customer + P.I waste Auping	(Polyethylene terephthalate, upcycling credit)[22]	Unit	kg CO2e saved
Saved CO2e for Virgin material	0.74	kg CO2e /kg	**7.33**
Saved on waste incineration[23]	1.35	kg CO2e./ kg	**12.06**
Total		**total**	**19.39**

Table 35. Indication for chemical recycling based on Idematapp 2020 upcycling credits

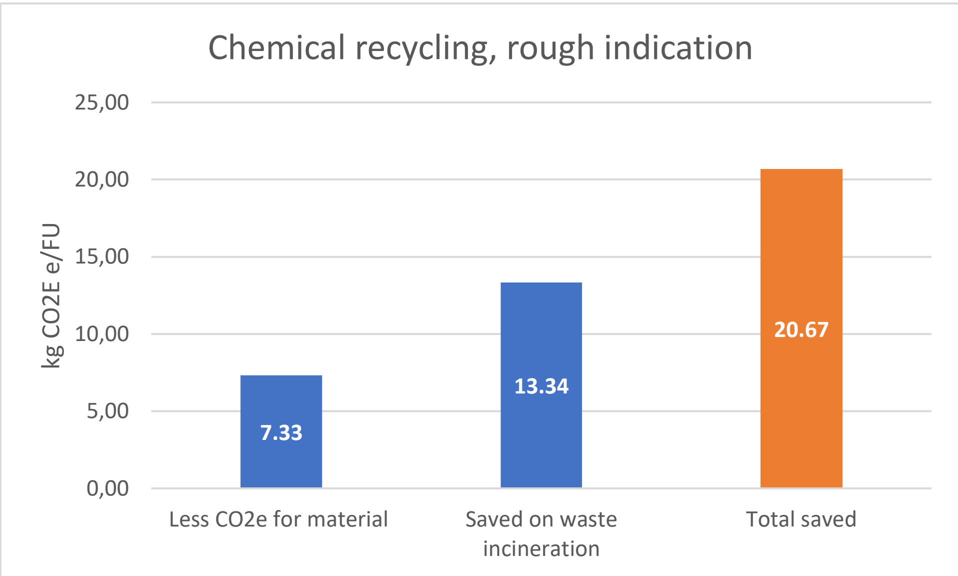


Figure 68. Rough indication based on Idematapp 2020 upcycling credits.

[22] From Idematapp2020 database
[23] Assuming a recycling rate of 90%. The remainder is assumed to be incinerated.

Appendix 11 Material waste

In this Appendix background information for the material wastes modelling is given. First, the rejected product rates are explained. Thereafter, the method used to approximate the process material waste is given.

Rejected product rate

The rejected product rate is not known for most processes. Therefore, literature is used to estimate this rate for textile process. A bedwear research of (Ahmed 2006), found that most of the evaluated producers, have a rejected production between 2% and 5%, in Pakistan. Another research in the US, mentioned a reject rate of 3.9% before a quality optimization process and of 2 % after. As far as known, all textile processes in this research take place in Europe. In this region, most companies are assumed to have optimized production systems. Therefore, in this LCA the rejection rate is estimated at 2 percent[24] for all textile processes. Besides, for foam and latex products, this number is estimated at 1%, by an expert. Lastly, for mattresses, the rejected product rate is set at 1,1%, taken from internal documentation (Auping 2020).

Process material waste

The material wastes for each process in this LCA are estimated as follows:

- If real waste data can be retrieved, this is used. This is the case for only a limited number of processes.
- The cutting waste at Auping for fabrics on a roll, are estimated[25] by two formulas:
  - Formula 12 for flat mattress layers. This formula does not yield for wide mattresses that do not fit two times in the mall (>100 cm), which is not the case for the FU in this LCA.
  - Formula 13 for the “Border layer” and “Thermoloft layer” that are processed on the Beckman machine.
- Most supplied fabrics are delivered to the manufacturer on a roll or as plate. For the fabric delivered on a roll, the fabric requires cutting to the right size at Auping. For the products delivered as plates, similar curtailing is done at the supplier. Therefore, for all components delivered as plate, the waste is assumed to be similar as at Auping.
- For all remaining processes that have an unknown waste, the average cutting waste of the other processes is taken.

For the processes that have known waste information, this data is used. For the majority of the process, no site specific waste data is obtained. For these layers, either data from researches is used, or expert estimates.

Most supplied fabrics are delivered to the manufacturer on a roll or as plate. For the fabric delivered on a roll, the fabric requires cutting to the right size. For the products delivered as plates, similar curtailing is done at the supplier. Therefore, for all components delivered as plate, the waste is assumed to be similar as at Auping. For all remaining processes that have an unknown waste, the average cutting waste of the other processes is taken.

[24] Only as estimate for unavailable data, If the real rejection product rate is known, that number is used.
[25] This formula is based on earlier internal research of F. Pekkeriet.

$$w_{m1} = (d_q - h_q) - 2 * (d_m * l_m) * (g_m/a_m)/2 \qquad (12)$$

Where

$$w_{m1} = Cutting\ waste\ estimation\ by\ mall\ size\ \ (kg\ waste\ material)$$

$$d_q = width\ of\ the\ mall\ used(m)$$

$$h_q = height\ of\ the\ mall\ used(m)$$

$$d_m = width\ of\ the\ mattress(m)$$

$$l_m = lenght\ of\ the\ mattress(m)$$

$$g_m = weight\ of\ mattress\ (kg)$$

$$a_m = surface\ size\ of\ mattress\ (m2)$$

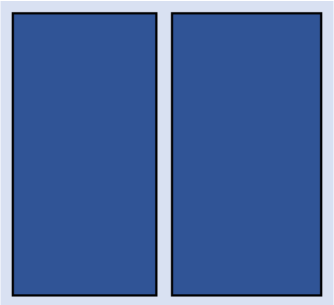


Figure 69. Schematic representation of the mall with two single mattresses. The light blue area indicates the cutting waste.

$$w_{m2} = (d_r - h_b) * 2 * (d_m + l_m) * g_m/a_m \qquad (13)$$

Where

$$d_r = width\ of\ roll\ (m)$$

$$h_b = height\ of\ the\ border(m)$$

$$d_m = width\ of\ the\ mattress(m)$$

$$l_m = lenght\ of\ the\ mattress(m)$$

$$g_m = weight\ of\ mattress\ (kg)$$

$$a_m = surface\ size\ of\ mattress\ (m2)$$

Appendix 12 Pedigree DQI score criteria

Indicator score	Very good	Good	Fair	Poor
Reliability	Verified data based on measurements from known sources	Verified data partly based on assumptions or non-verified data based on measurements	Non verified data partly based on assumptions or qualified expert estimate	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered. Or collected from the supplier that is concequently the supplier of the studied good. Measured over an adequate time period	Representative data >50% of the sites in market. Or collected from one supplier that most likely will be supplying for the next years.	Representative data from only some sites (<50%) relevant for the market considered or> 50% of sites but from shorter periods	Representative unknown or data from a small number of sites and from shorter periods. Or surrogate data from one factory.
Temporal correlation	≤ 3 years of difference to year of study	3 to 6 years difference	5 to 10 years difference	Unknown or ≥10 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with more or less similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data that has different materials or processes and different technology

Table 36. Modified DQI criteria table of (Weidema and Wesnaes 1997)

Appendix 19 packaging volume efficiency

Package efficiency of on roll transportation

Most of the fabrics are delivered on rolls. These rolls are either delivered in a plastic foil, or delivered in a cardboard box. As shown in Figure 73a and 74b, there will always be a certain loose space for the packing of rolls. For the transportation modelling of rolls in this report, the loose volume is approached as indicated by the grey area in Figure 73e. Formula 15 is used to estimate this roll volume efficiency, where v_e denotes the estimated volume efficiency for roll transportation. Independent of the stacking method, there will always be a lost volume for roll transportation. The same formula can be used to approach the volume use of rolls transported in cardboard boxes.

$$\eta_t = \frac{1-(d^2-\frac{1}{4}d^2\pi)}{d^2} = 79\% \qquad (15)$$

Where

η_t = *The packaging volume efficiency for goods t (-)*

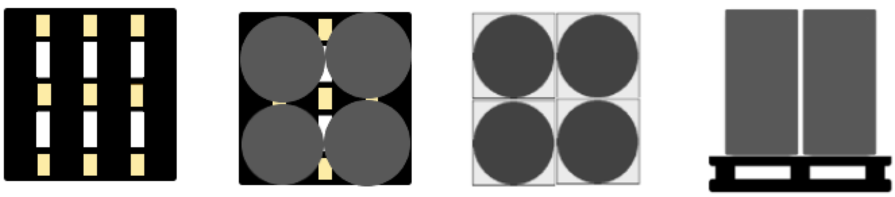
d= Roll diameter (m)

(a) **(b)** **(c)** **(d)** **(e)**

Figure 73. Estimated volume efficiency for rolls

Packaging volume efficiency pocket spring rolls on pallets

Pocket springs are also packed on a roll. However, these rolls are transported vertically on a pellet. Formula 15 still yields for the spaces around the roll, see Figure 74c. However, the space the pallet requires is loose space. Therefore, a correction shall be made for the loose space the pallet takes, see 74d. The height of these pallets is 14cm, the rolls for this type of mattresses have a height of 85 cm. As a result, for all pocked springs, the packaging volume efficiency is assumed to be 66%.



(a) **(b)** **(c)** **(d)**

Figure 74. Estimated volume efficiency for rolls of pocket springs on a pellet

Packaging volume efficiency of transported plates

The transport of fabrics and foams plates, are modelled in a different way. Depending on the mattress dimensions, the layers in the core of the mattress have different sizes. Most of the layers are transported in carboard boxes on a pallet. A simplified illustration of this transport type can be found in Figure 75 For practical reasons, the following assumption are being made:

- The various fabric or foam layers inside the mattress are the same size as the mattress. 0.90 for the specific mattress in this research.
- For the sizes of the pallets, 5 pellets used for this purpose were measured at Auping. The average width was 1 meter
- The share of loose spaces are estimated by the surface as follows:
    - 0.10 x 1.80 = 0,18 m2
    - 0,14 x 1.00 = 0.14 m2
- Then the packaging volume efficiency could be calculated by:
    - 0,32 / (1.00 x 1.80) = 82.2 %

As a consequence, the packing volume is defined as 82% for the transportation of plates.

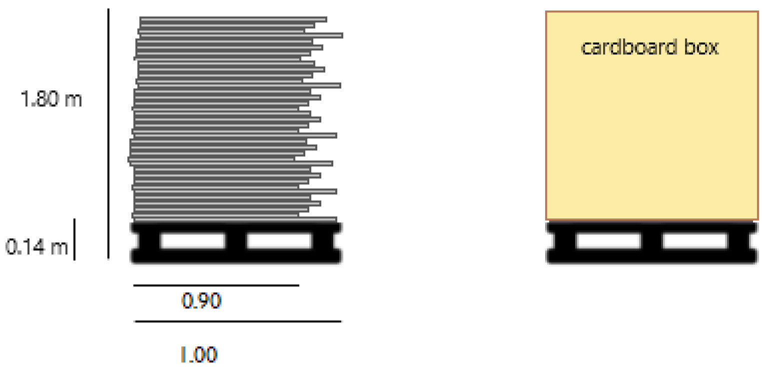


Figure 75 plates of foam and thick fabric transported on a pellet.

Appendix 21 Sankey diagram Mattress recycling

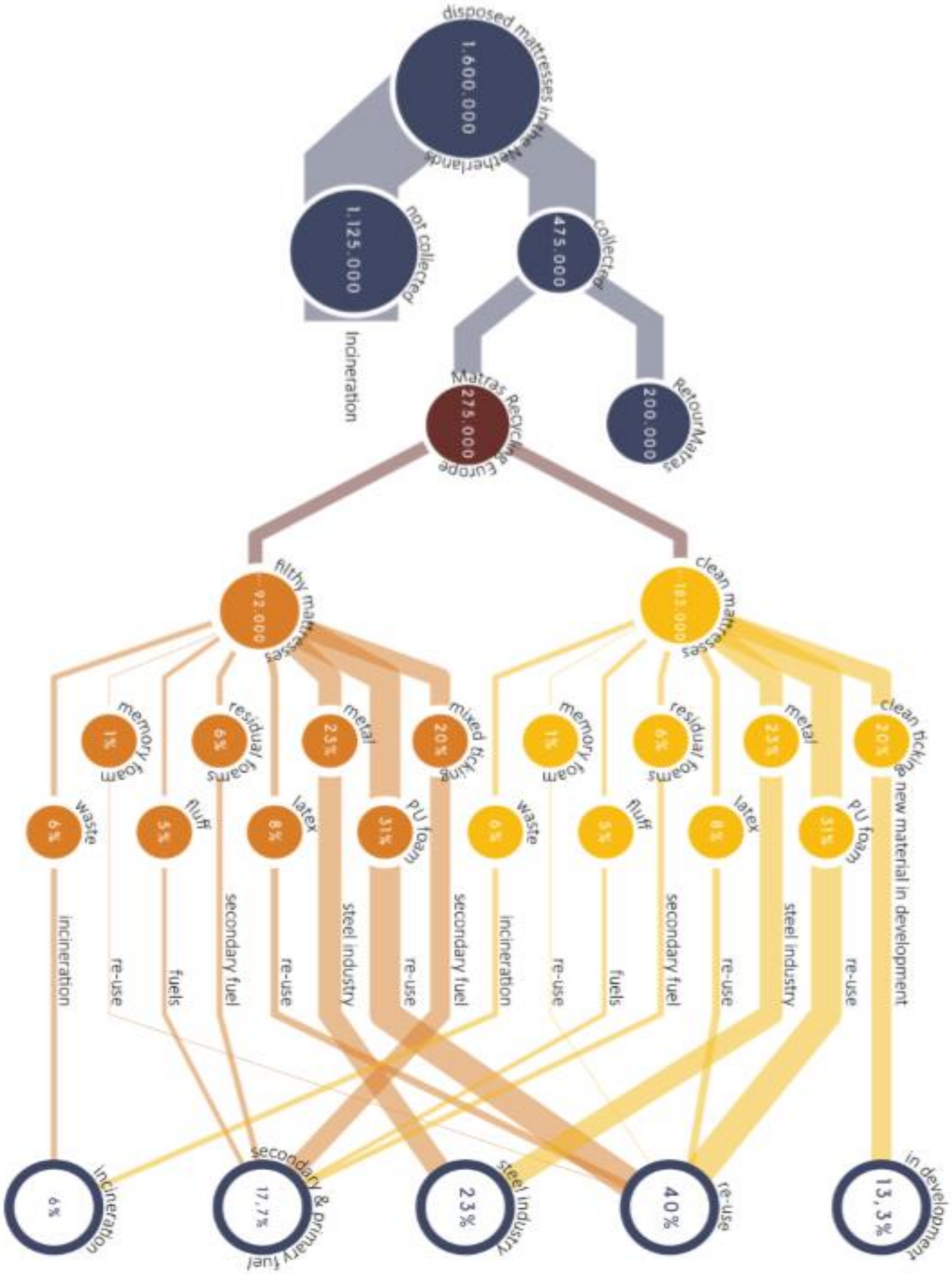


Figure 77. Sankey diagram for Mattress recycling Europe. From (Narinx 2016)