PAVE THE WAY TO SUSTAINABLE CARPETS

Designing alternatives to increase the sustainability of the Dutch carpet industry

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Pave the way to sustainable carpets

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PREFACE / ACKNOWLEDGEMENTS

This thesis marks the final step in my academic career, which started over eight years ago in Delft. With much pride and joy I look back on a fruitful period in which I developed into a professional academic and made ever-lasting friendships along the way. Even though I briefly left Delft to obtain a second master's degree in Leiden, Delft never lost its appeal to me. Returning to the Delft University of Technology felt like returning home and I will always consider myself to be an proud TU Delft engineer.

Although this master's thesis is primarily aimed at the carpet industry, many of the findings carry over to other industries that have a troublesome end-of-lifecycle product. It is thus not only aimed for the carpet industry, but for all that have an invested interest to increasing the sustainability of environmentally straining industries. This thesis was an individual project conducted at the Delft University of Technology, but was aided by a few academics and people from the industry.

I would like to express my gratitude to both Dr. Steve LeMay and Ir. Eline Oudenbroek for aiding in what became my thesis. Due to the COVID-19 pandemic your extra effort to help me in my graduation effort are much obliged. Likewise, my gratitude goes out to Dr. Marilyn Helms for her valuation effort and Gert Sterk, Wim de Jong and Ton van Winden for their insights in the carpet incineration process. But without my supervisors, this thesis could have never been realized. In a time where the COVID-pandemic was at its peak and required much adaptation of all teaching staff, my supervisors and chair still found the time to commit to my thesis. A special thanks to the Director of Studies Dr.ir. Ivo Bouwmans for his guidance when it I was about to give up on this topic when an internship opportunity at Interface went bust. This was before he agreed to chair my committee. This committee is completed by Ir. Marcel Ludema, first supervisor, and Dr.ir Jaco Quist, second supervisor whose time and guidance are also greatly appreciated.

Finally, I would like to express my greatest gratitude to the people close to me. This gigantically time-consuming thesis posed a strain on many of my personal relationships in these extraordinary times. Secluded from the outside world I would work on this thesis until deep in the early mornings, limiting all social interactions. Regardless, my friends and family were there for me whenever I needed them. Thanks to my former study companions which I kept bugging with thesis related questions long after they have graduated. And a special thanks to my parents and girlfriend for their continuous support. Without your unconditional love none of this would have been possible.

Get well soon grandpa. You are doing a kick-ass job in beating your caner.

Jay Jay Kleinendorst
Arnhem, November 2020

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SUMMARY

With an undesirable end-of-lifecycle product, the carpet tile might be one of the most unsustainable products that the textile industry produces. It is common practice to landfill a carpet tile at its end-of-lifecycle, which is after just 10 years of use. A carpet tile is constructed out of high value resources like nylon and different plastics, but there appears to be little to no recycling effort. And with the Netherlands ranking as one of the world's top tier carpet producers, this puts a big strain on the Dutch environment. Growing environmental regulations by the Dutch government make for a technology pull by the industry, desperately seeking ways to increase sustainability. This thesis aims to design ways to aid the carpet industry through answering the following research question:

What measures are available to develop a sustainable supply chain for the Dutch carpet tile industry by the year 2030?

This thesis set out to explore the supply chain of a carpet production and identify areas where sustainability could be increased. But it was soon discovered that this chain is a mere ad-hoc construction, driven by public image rather than actual sustainability. This made for the very first step in this thesis to be an identification and mapping of the current, and optimal, supply chains. Once this concept was established, measures are identified through literature studies that could increase the sustainability of the industry. These measures are quantified in a computational model that expresses the emissions and energy requirements of the cradle-to-grave lifecycle of a carpet tile. These measures are bundled into solutions through morphological charts to form multi-facet sustainability increasing solutions. With the performance of these solutions known, the likelihood of adaptation of these measures is examined. This is achieved through a scorecard that was established in cooperation with a carpet manufacturer. Based on these multi-criteria analyses, a policy advice is issued, and possible governmental intervention is discussed. The finished product is a framework that generates and evaluates sustainability increasing measures on their effect and likelihood of adaptation by the industry. The created model was found to be solid and will be made available to the industry as well.

The first exploration of the supply chain a few issues were discovered, especially given the fact that the industry strives to achieves full circularity. In terms of EOL product, a carpet tile is valuable and worthless at the same time. Carpet tiles are created out of several high value resources that are relatively easily recyclable in pure form, but in a carpet these resources lose all their value. The recycling of these resources is more costly than acquiring the same resources from virgin (exhaustible) sources, thus no recycling system is established. Dutch waste incineration plants cannot process carpet as it releases too much energy, and with that, carpet tiles can only be landfilled at the end of their lifecycle. Adding to the

losses of carpet tile production is the failing logistic policy of carpet manufacturers. In aims of achieving circularity, some EOL carpets are collected by Interface and Tarkett/Desso. But with no processing power available, all this policy achieves is to create extra transport emissions and costs. A testament to this failing policy is the recycling of nylon fishing nets by Interface. Since no supply of fishing nets was found locally, Interface's "Net-Works" program imports EOL fishing nets from the Philippines, processed in Slovenia, which is transported through Italy to the Scherpenzeel plant. A 18,000 km transportation operation for a resource that is also manufactured in the Netherlands. The industry shows willingness to increase its sustainability, but without a market or purpose for EOL products, sustainability is hard to increase. The following high aggregate level supply chain was created as a representation of the current logistic processes:

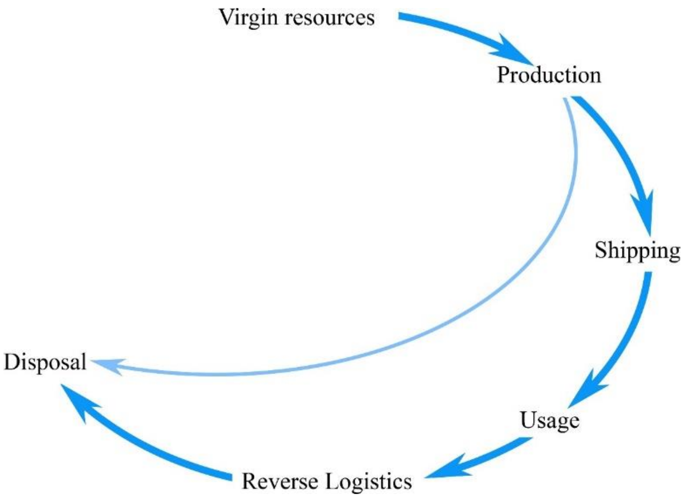

Figure I. Current supply chain carpet tile industry.

With this supply chain, a model was created to calculate the effects of the inability of the industry to recycle or downcycle their waste product. The following costs were identified in the production of one carpet tile (0.25 m^2):

Table I

Environmental costs of producing one carpet tile

	Production		**Shipping**		**Disposal**	
	Virgin resources	Manufacturing	To customer	From customer	Landfilling	TOTAL
kg CO_2-eq.	3.6	0.2	0.1	0.1	0.8	4.9
MJ	72.0	3.5	1.3	1.1	0	78.0
mg PM_{10}	0	11	5	4	0	20

In the literature and through creative thinking, several ways were discovered to decrease these costs Three stages were identified where the biggest gains in sustainability can be achieved. These are the production stage, transportation stage and waste processing stage. The following solution space was generated, with the calculated effects:

Table II

Solution space & effects on sustainability

	MEANS 1	MEANS 2	MEANS 3	MEANS 4
PRODUCTION	**ZE-manufacturing** -3.5% CO_2-eq. 0% MJ -53.9% PM_{10}	**ZW-manufacturing** -1.0% CO_2-eq. -1.0% MJ -0.7% PM_{10}	**ZE-recycling** 0% CO_2-eq. 0% MJ 0.0% PM_{10}	**ZE-resources** -74.7% CO_2-eq. 0% MJ -53.9% PM_{10}
TRANSPORTATION	**Relocation** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	**ZE-transport** -2.3% CO_2-eq. -2.3% MJ -4.6% PM_{10}	**Local collection** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	
WASTE	**Incineration** -2.2% CO_2-eq. -26.3% MJ +45.4% PM_{10}	**FRC** -5.4% CO_2-eq. -0.1% MJ +2.6% PM_{10}	**Insulation** -24.4% CO_2-eq. -6.6% MJ +2.6% PM_{10}	**Full circularity** -81.3% CO_2-eq. -81.4% MJ +14.9% PM_{10}

One of the most frequent listed alternatives to carpet landfilling is the use of nylon fibers to create Fiber Reinforced Concrete (FRC). This study ill-advises the downcycling of carpet tiles into FRC due to two reasons. FRC uses nylon fibers (a high value product) to reinforce concrete (a low value product). As only the nylon fibers are reused, all other material of the carpet tile still needs disposal. Unlike regular concrete, FRC cannot be repurposed and needs disposal at its EOL. This increases the landfill potential of an FRC-downcycled carpet tiles from 2.65×10^{-3} m^3 to 1.20×10^{-2} m^3, thus not only causing a delay of environmental effect, but also increasing it. Insulation was discovered to prove a viable alternative, if nylon is able to replace rockwool.

A few factors were identified with the industry that dictate if a sustainability increasing measure is adapted. These factors relate to resilience, financial stability, logistic efficiency and the public image.

Through a multicriteria-analysis, it was discovered that a combination of zero-emission manufacturing, decentralized EOL carpet tile collection and insulation downcycling yields the best results and is the most likely to be adapted by the industry. This solution requires the usage of renewable energy sources for the production of carpet tiles, such as solar or wind energy. It also requires the manufacturing process to reuse any generated heat and prevent particulate matter from being released into the environment. The decentralized collection requires carpet tiles to be recycled at local waste processing plants, limiting the reverse logistics. These plants separate the nylon fibers from the carpet tile´s backing material, and the fibers are sold to local insulation/construction companies.

The most important improvement however is considered to be a policy adaptation to facilitate a change in problem ownership. When a carpet tile is sold, the product becomes the (financial) responsibility of the user. The Dutch government facilitates carpet disposal, often free of charge. So, the manufacturer is not carrying any of the costs associated with the disposal of these carpets. This creates a lack of incentives for the carpet manufacturer to produce carpets that easier to recycle or dispose. With the suggested leasing- and deposit structures, the policy advice is to make the manufacturer owner of the EOL product again.

It would however be deemed unfair to assign all responsibility for the establishment of this new system to the carpet manufacturer, as the major beneficiary to this system is the government. With their vast network of resources and wide experience, the Dutch government can cooperate in the establishment of this new carpet recycling policy. Equipping all 355 Dutch municipal recycling plants with carpet tile shredding and separation machines will cost upwards of two million euros. If this cost is assigned to the carpet industry, the acceptance for this system would suffer. Thus, a cooperation is required between the government and the carpet industry to establish this new system of carpet disposal.

With the cooperation of the industry and the government, a financially sustainable and more environmentally friendly processing method of EOL carpet tiles can be established. This is however a far cry from the optimal closed-loop sustainability. Within the set timeframe, taking the current production methods in mind, achieving a fully sustainable carpet supply chain is deemed impossible. Only when carpet manufacturers start producing more easily recyclable products, a fully sustainable, circular, industry can be established. Until this fully recyclable carpet tile is created, the processing of EOL carpet tiles will remain more of a damage control operation rather than a sustainability increasing operation. The road to a fully sustainable carpet tile is still long and most certainly not paved with the current generation of carpet tiles.

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LIST OF ACRONYMS AND ABBREVIATIONS

CO_2-eq.	Carbon dioxide-equivalent emissions
EOL	End-of-Lifecycle
EPD	Environmental product declaration
FRC	Fiber Reinforced Concrete
GER	Gross Energy Requirement
GHG	Greenhouse gas(ses)
GJ/MJ	Gigajoule/Megajoule
GWP	Global Warming Potential
KPI	Key Performance Indicator
PET	Polyethylene terephthalate
PM_c	Particulate Matter
PWR SRC	Power source
RES	Resource(s)
RL	Reverse logistic
RoI	Return on Investment
SCM	Supply Chain Management
Sep.	Separation
TEU	Twenty foot equivalent unit
tkm	Tonkilometer
VCM	Value Chain Management
ZE	Zero Emission
ZW	Zero Waste

1 INTRODUCTION

Structure

This chapter introduces the industry, the changing climate and the challenges the carpet industry is facing. In section 1.1, background information is presented as the origin of the need for sustainability. Section 1.2 discusses the need of making the carpet industry sustainable. Section 1.3 discusses the thesis outline.

1.1 BACKGROUND

The carpet industry is known as one of the most polluting industries worldwide (Kant, 2012; Khan & Malik, 2014; Choudhury, 2014). The traditional carpet production process is deemed extremely polluting, toxic even, and the waste product is barely recyclable (Choudhury, 2014). This results in the carpet industry forming a disproportionally big source of waste (Fishbein, 2001). Compared to absolute national waste figures, the carpet industry is responsible for 2% of the total municipal solid waste in volume, or 1% in weight (Fishbein, 2001). This waste primarily ends up in landfills, arguably the least sustainable disposal method (Miraftab, Horrocks & Woods, 1998).

The Netherlands is a top-tier producer of carpets, ranking the world's second biggest exporter of carpets worldwide in 2003 (Centraal Bureau voor de Statistiek, 2005). Bulky, complex and composed of different materials, carpets pose a real challenge in terms of recycling. Carpet tiles are even more unsustainable than regular carpets due to a more complex material composition. With strict regulations regarding emissions and recycling on the horizon for Dutch industries (Nijpels, 2018) and with a waste product that is hardly reusable an important question arises: how will the Dutch future proof the carpet industry?

1.2 PROBLEM DESCRIPTION

The wish for a sustainable supply chain is widely expressed by the industry (Rusinko, 2007; Choudhury, 2014; Khan & Malik, 2014). This has primarily led to technical innovations that streamline the production process. In wake of the technology pull for recycling or downcycling methods, some carpet manufacturers have started reclaiming carpets that are at their end of usage, also known as end-of-lifecycle (EOL) carpets (Deutsche Umwelthilfe, 2017, February; Vogels, 2019; E. Oudenbroek, personal communication, Feb 17, 2020). Remarkably, this technology pull has gone unanswered. Reclaimed carpets remain in storage and with every carpet manufactured, more waste is created. This makes for a complicated and unclear logistical process, as it is unknown to what purpose EOL carpets are reclaimed. Due to this uncertainty, no clear overview of costs for both the entire supply chain and the reverse logistic processes can be established. Manufacturers feel the need to recycle their EOL product, but their reverse logistic operations are halted due to a lack of processing power. By primarily seeking full circularity, which is financially unachievable, other options for establishing a sustainable supply chain may be overlooked.

1.3 RESEARCH QUESTION & SUB QUESTIONS

There seems to be a universal consensus that carpets still have value at their end-of-lifecycle and thus should be reused or recycled. This would require demand for the product, an effective form of collection and a well-established logistical chain that allows for distribution of the recycled or downcycled materials. These factors are all currently lacking, posing a (potentially unnecessary) high environmental strain. Circular economics as a universal concept has proven to be highly beneficial to some sectors, but there is little to no insight in if (effective) circularity can be achieved by the carpeting industry. Furthermore, it is highly unknown if the collection of used carpets would be beneficial at all for reducing emissions, as circularity might even increase emissions. As such, a design challenge is identified on how a sustainable supply chain could be achieved to reduce emissions for the carpeting industry. This makes for the following research question:

What measures are available to develop a sustainable supply chain for the Dutch carpet tile industry by the year 2030?

Because of the broad and complex nature of this research question, there should be no assumption that the research question can directly be answered in a straightforward manner. The problem-driven design challenge is derived from knowledge gaps regarding the production process, reverse logistics and sustainability in the carpeting industry. Design studies are found to be “complex, multivariate, multilevel and interventionist, making warrants particularly difficult to establish” (Shavelson, Phillips, Towne & Feuer, 2003, p. 25). Furthermore, they tend to “rely on narrative accounts” (Shavelson et al., 2003, p. 27). The lack of scientific and public information is one of de defining characteristics of the search for sustainability in the carpet industry. In order to overcome the complexity of the proposed research, sub questions are created to be able to reach a comprehensive conclusion to the main research question. The following sub questions have been formed:

1. *What is the logistical path of one unit of carpet tile, from production to EOL (cradle-to-grave)?*
   The first sub-question aims to map out the current cradle-to-grave process of a carpet tile, in order to evaluate which areas or processes have the potential of gaining sustainability. This is achieved through a literature study and through semi-structured interviews with members of the supply chain.

2. *What are the environmental costs of one unit of carpet tile, and how much energy is required by the logistical chain?*

   In order to assess the gains of potential sustainability increasing measures, an overview is to be established on the (logistical) costs of the current cradle-to-grave lifecycle. This will require the establishment of a modeling tool. An (imitation) experiment is conducted with the model to simulate the current scenario. This results in a two-step approach to this research question:

   A) *Establish a model*
   B) *Use model to estimate environmental effect of the current carpet supply chain*

3. *What options are available to establish a sustainable supply chain?*

   The third sub-questions continues on the findings of the first sub-question. With known failing or less-than-optimal performing processes mapped, tailor made solutions are designed that have the potential to increase the sustainability of this process. This design process relies on narratives, literature and draws on the findings of the model.

4. *What is the effect of reverse logistics on the supply chain, and how can this be used to improve the sustainability?*

   Reverse logistics was identified in the current literature to be a key element to increasing sustainability. This sub-question aims to assess the impact of a reverse logistics policy on the total sustainability of the supply chain. This is done through a simulation study using the earlier created model.

5. *What are the success and failure factors to a sustainable supply chain, what policy is required to guarantee its success, and is governmental intervention needed?*

   It is an oversimplification to assume that the best performing alternative is always preferred. This sub-question explores what factors make for an acceptable solution by the carpet industry. The goals of the industry are examined to form a list of criteria that dictate the acceptance of a sustainability increasing measure. Based on these findings, through a multi-criteria analysis, the best performing measure is selected. A policy advice is issued to guarantee the optimal usage of this measure.

1.4 THESIS OUTLINE

This paper aims to design means that would increase the sustainability for the carpet industry within a relatively short time span. Through analyses of the current and possible future supply chains, a cost/benefit estimate can be established based on different recycling alternatives. A computational model is created for the study, but it will also be sent to the industry to possibly benefit from it. The results of this model are used to create a policy advice on the best way forward for the carpet manufacturers and all involved. This study approaches the design methodology according to the instructions of Dym, Little & Orwin (2004). The next chapter, chapter 2, will discuss the thesis methodology. This chapter will first describe the currently established pool of scientific knowledge through a literature study, and how this knowledge can be used in the answering of the research questions. Knowledge gaps are identified and methods are proposed in which this study aims to further expand this pool of knowledge. Chapter 3 discusses the problem in greater detail, and a conceptual model is presented. This conceptual model is converted to a preliminary design in chapter 4 through a list of requirements and key data points. This leads to a detailed design of the modelling tool in the end of chapter 4, and its usage to calculate the current costs of carpet industry. In chapter 5, possible sustainability increasing measures are designed and presented. Before chapter 7 rates these measures and provides a policy advice, the model and the modeling results are validated in chapter 6. This thesis comes to an end in chapter 8, presenting a conclusion and an advice on future studies.

2 THESIS METHODOLOGY

Structure

This chapter discusses the approach and methodology of this thesis as well as presenting some boundaries to the set solution space. It does so by first presenting the research approach in section 2.1. Section 2.2 presents some valuable insights that arose during a literature study. Section 2.3 will discuss the scope and demarcation: what will be included within this research, and what will be left outside of consideration. Section 2.4 is aimed to introduce some concepts that were found to be of importance, and which will be used throughout the design, serving as the framing of some concepts. Section 2.5 discusses the methodology of this design-based research. Following the methodology, section 2.6 discusses the research aims and deliverables. This chapter concludes with section 2.7 in which a graphical display of the research flow is presented.

It is identified that the carpet industry poses a disproportionally big strain on the environment. There is a need by the industry to improve its sustainability, but this seems to go unanswered. This thesis set out to discover how this sustainability can best be achieved. As there are several approaches to this problem, this chapter establishes a methodology. It describes what is already known, what system boundaries are considered, and how the thesis approaches the problem of lacking sustainability in the carpet's supply chain.

2.1 RESEARCH APPROACH

This thesis creates implementable options for the carpet industry to improve its sustainability. It combines findings from different sources into a new solution. This makes for a design approach. In order to come to a suitable design, a mixed-research method is applied, as well as the design methodology as described by Dym et al. (2004). To identify the opportunities and a possible solution space, a literature study is conducted. Through the obtained data and insights from this literature study, an (imitation) experiment will be constructed using a modeling approach. Excel will be used as the tool/modeling environment for this model. With the quantification of the identified means, a multi-criteria analysis is applied to rate the different means in order to form a policy advice. Both industry validation and expert validation is applied to some of the products created in this process. This is achieved through semi-structured interviews. The following experts were consulted:

E. Oudenbroek: Vice President Operations at Interface Europe Middle East and Africa

Dr. S.A. LeMay: Associate professor of marketing, supply chain logistics and economics at the university of west Florida

Dr. M.M. Helms: Professor of logistics and supply chain management at the Dalton State College

G. Sterk: Head plant performance & engineering at AVR waste disposal

T. van Winden: Chemical engineer at ARN BV waste disposal

W. de Jong: Advisor market and strategy at Twence waste disposal

2.2 LITERATURE STUDY

To gain a better understanding of the carpet industry and its logistic processes, a literature study was conducted. It was discovered that there are two schools of thought in regard to increasing the sustainability of the carpet industry. Many researchers advise improvements to the carpet coloring techniques (Capar, Yetis & Yilmaz, 2006; Shaikh, 2009; Chinnasamy, Bhatnagar, Hunt & Das, 2010; Kant, 2012). Research by Soleimani-Gorgani & Taylor (2008) suggests solution-dyeing fabrics, compared to piece-dyeing fabrics, as it both increases the durability as well as eliminates a big amount of waste (water). Solution-dyeing process is currently the best practice in carpet manufacturing. This leaves little room for improvement. The second group of researchers focused on the waste product, EOL carpets, in terms of its potential and value. They indicate that EOL carpets have value and that a market could even be established for the EOL product but is hindered by technological limitations and a poor infrastructure (Miraftab et al., 1998; Peoples, 2006; Cline, LeMay & Helms, 2015). As some of this literature is 22 years old and advices on technological advances, new opportunities are assumed to be available to increase this sustainability. This research continues on the assumption that a market for EOL product could be established and explores in what way this can be achieved.

With this newly obtained direction, a second literature study was conducted. It was identified that one of the world leading carpet manufacturers, Interface, uses downcycled nylon fishing nets to produce some of its carpets (Nelson, 2009). This nylon originates from the Philippines (Khoo, 2018), some 18.000 km away from the production facility in Scherpenzeel. This confirms the findings of Cline et al., (2015) that argues for the establishment of a better infrastructure for the carpet industry. This includes a reverse logistics policy for the collection of carpets (Fleischmann, 2003; Cline et al., 2015). Through this reverse logistics policy, financial gains can be achieved by the manufacturer (Winkler, 2011; Kinobe, Gebresenbet, Niwagaba & Vinnerås, 2015) while at the same time increasing customer service (Sharma, Panda, Mahapatra & Sahu, 2011). Research indicates that a closed-loop supply is the ultimate way to ensure sustainability (Winkler, 2011). However, as discovered earlier, this closed-loop supply chain is difficult to achieve (Helms & Hervani, 2006). In fact, Helms and Hervani (2006) argue that there is hardly a demand for used carpets. This causes bad resource management and results in many carpets being disposed (Hosseini, Chileshe, Rameezdeen & Lehmann, 2014; Sobotka & Czaja, 2014). The establishment of a well setup (logistical) infrastructure is thus required in order to facilitate the reuse of carpets (Realff, Ammons & Newton, 1999; Biehl, Prater & Realff, 2007; Helms & Hervani, 2006; Cline et al., 2015).

For uses of EOL carpets, only one widely researched use was identified in the literature: Fiber Reinforced Concrete (FRC). In FRC, a carpet's nylon fibers are extracted from EOL carpets and are used to strengthen concrete (Wang, 1999). Concrete is however a low-value product, and thus by downcycling carpet into concrete, logistic value is lost. With that, whereas regular concrete is fully recyclable, FRC is not. This makes for an even bigger landfill potential of FRC recycled carpets (Naqvi, Prabhakara, Bramer, Dierkes, Akkerman & Brem, 2018). An extensive search for other downcycling options led to the discovery of the possibility to use EOL carpet tiles as insulation material. Carpets are (partially) known for their heat insulation properties. Likewise, wool is one of the traditional materials used in the insulation of mountain cabins. This led to the identification of a downcycling use of EOL carpets as insulation material. Literature suggests discusses nylon as being too expensive for insulation purposes and relatively little is unknown about its heat conducting properties (Alam, Singh & Limbachiya, 2011).

For disposal of EOL carpets, two methods were identified. These are landfilling and waste incineration, both with distinct advantages and disadvantages. Landfilling is currently the only option for Dutch carpet waste, but with a high calorific value, the incineration of carpet could possibly generate gains in terms of energy regeneration (G. Sterk, personal communication, August 14, 2020). The glass, paper and bottle recycling industries were identified as possible applicable analogies. It was identified that product-service systems could aid in increasing sustainability if unclear problem ownership is one of the issues in regard to recycling (Baines et al., 2007).

Energy sources are found to be a focus point of the carpet industry. Interface treats any non-renewable energy used in the fabrication process as "waste" (DuBose, 2000). The (obvious) means of producing and recycling carpets based on renewable energy sources is then to be included in the solution space, but also the usage of transportation means that use renewable energy. Furthermore, considering energy in terms of waste refers to the zero waste movement. An equally important aspect in the zero waste movement is zero waste manufacturing (Kerdlap, Low & Ramakrishna, 2019). In carpet manufacturing, this waste consists of trimmings and cutting waste, which are identified as a source of value losses in the production chain. Likewise, it can be concluded that the construction of a carpet out of fully renewable resources, thus creating a zero-waste resource source, is a measure to increase the sustainability of the supply chain.

The government has an invested interest in making the carpet industry more sustainably. It currently considers EOL carpet as a high value, unusable, product (Koppert & Römgens, 2012; Ministerie van Infrastructuur en Waterstaat, 2019, July). Investment strategies are discussed which could aid the carpet industry become more sustainable. A policy advice was issued to the government, suggesting the financing of sustainability increasing measures for the carpet industry (de Baedts, 2012, may).

It can be concluded that there are possibilities for the carpet tile industry to have a sustainable supply chain. But these opportunities are not yet sufficiently explored. This leads to ad-hoc and ineffective recycling efforts by carpet manufacturers. In order to achieve greater sustainability, an efficient infrastructure needs to be established. This includes the reverse logistics effort, as well as an EOL product processing capacity. The costs and method to achieving this infrastructure are unknown. The value of end-of-lifecycle carpets also proved to be a big source of uncertainty. Without a downcycling or recycling use, returning EOL carpets to the manufacturer is a wasted effort. And without a market for this EOL product, disposal is the only alternative. If the government could aid in the establishment of such a market is largely unknown as well. It is to be concluded that both the industry and the government could hugely benefit from an academic investigation into possible recycling/downcycling options, the costs/benefits of these options, and a policy advice.

2.3 SCOPE & DEMARCATION

When creating a conceptual and computational model, scoping is an important aspect and it will be thoroughly discussed. This paragraph will discuss the system boundaries, which is not to be mistaken for modeling assumptions. These modeling assumptions will be discussed in chapter 4.

The first system boundary is formed by a geographical demarcation. This study will model and calculate effects based the Dutch market for the mainland of the Netherlands. This demarcation allows for a more accurate environmental assessment as it facilitates the usage of national (averaged) key figures (Romijn & Renes, 2013). It further allows for a less complicated adaptations of policy, removing the issue of conflicting policies across nations, as well as limits production/capacity distribution challenges and a possible lack of data.

This study only considers carpet tiles, not wall-to-wall carpets. This is largely accredited to the fact that carpet tiles are more environmentally straining than regular carpet (more thoroughly discussed in chapter 3.1). But carpet tiles also offer more opportunities in terms of sustainability. In case of damage, a single carpet tiles can be changed whereas for regular carpet, the entire carpet unit needs replacement. Carpet tiles also produce less waste during the installment phase. And through its uniform size, this waste has more potential to be recycled as flooring for other areas. Adding to this is the advantage of transport, where carpet tiles can be tightly stacked and transported more conveniently, allowing for smaller means of transport. In terms of sustainability this means that carpet tiles have a greater reverse logistic value, as better capacity utilization leads to lower return costs.

Geographical locations, the origin of the carpet tile and its destination, form the next demarcation. The Netherlands is host to two world leading carpet tile manufacturers. These are Tarkett/Desso (Waalwijk) and Interface (Scherpenzeel). Two more manufacturers of carpet tiles have been identified within the Netherlands, being Condor Group (Hasselt) and Belakos flooring (Genemuiden). Condor group is one of Europe's biggest carpet producers with a vast variety of products and with goals similar to Interface and Tarkett. Belakos flooring is mainly aimed at the Dutch market and does not appear to recycle EOL carpets. Although these manufacturers also produce carpet tiles, their main focus are regular and automotive carpets. For these reasons, both the Condor Group and Belakos are not featured as primary focus points.

Governmentally approved key figures, or key figures from industrial standards, are preferred over otherwise scientific key figures. Modeling assumptions will be discussed in greater detail in chapter 4, as well as in appendix F. As discussed earlier, and as indicated by the scoping of the Dutch nation boundaries, these key figures will represent Dutch averages, and will be presented in euros. Emissions will be discussed in CO_2-equivalent units, a commonly accepted calculation tool that expresses all emissions in terms of global warming potential (GWP) (Heijungs, 2005). Particulate matter (PM_c) is also considered and is presented in a PM_{10} emission figure. This way an attempt is made to quantify the effects of all emissions (greenhouse gasses and PM) in a non-exclusive manner. These key figures will originate primarily out of scientific sources and are discovered through literature studies. Highly reputable sources like CE Delft and governmental departments are primarily used. Appendix F provides a full overview of the origins of all key figures that are used.

Sustainability is a broad and wide concept. This study maintains a definition of sustainability as defined by Elkington (1998). It considers three aspects: people, planet and profit, or in other words: social, financial and environmental sustainability. Sustainability needs to be paired with the upkeeping of financial stability (Fisk, 2010). Within this research, the main focus lies on the planet and profit aspect of sustainability. This demarcation is the result of a thorough consideration and analysis of factors that make up for social stability. A list of examples for social measures as found by Slaper & Hall (2011) include unemployment rate, female labor force participation, commute time, violent crimes per capita and health-adjusted life expectancy. An earlier scope set the boundary of the system to the Netherlands, known for a high living standard (Drobnič, Beham & Präg, 2010). Child or slave labor and excessive working hours are strictly forbidden within the European Union and specifically within the Netherlands. As such, after careful consideration and taking all system boundaries into account, it was opted to make the disputable assumption that the "people" aspect of sustainability within the Netherlands is widely protected by laws and best practices, and as such requires little focus.

As the literature identifies, the dyeing process of carpet is heavily environmentally straining. The current generation carpets are however dyed in a more environmentally friendly method, also increasing its durability. Current nylon carpet tiles start off as Caprolactam, a chemical (organic) compound. Through extrusion this Caprolactam is polymerized into polyamide 6 (nylon-6). Pigments are added in this polymerization process to create colored nylon. This requires less water and pigment than traditional carpet dyeing. The costs of coloring are marginal. One carpet tile requires roughly 6.87×10^{-4} to 3.43×10^{-3} grams of pigment, depending on the color (Soleimani-Gorgani & Taylor, 2008). This environmental effect is included in the model. Interface also uses this process to color and create new nylon out of EOL fishing nets (Anbumozhi & Kimura, 2018). This coloring operation takes place in Slovenia by the Italian company Aquafil (Luqmani, Leach & Jesson, 2017; Anbumozhi & Kimura, 2018). The fishnets themselves originate from the Philippines (Khoo, 2018). These effects (and transportation distances) are included when modeling downcycled nylon resources.

Finally, this thesis suggests achieving full implementation of the generated measures by 2030, ten years from now, whereas the "klimaatakkoord" gives the industry 30 years to limit their emissions. This is not necessarily done to pressure the industry into early results, but rather to leave the industry enough time to focus on other aspects of sustainability. The set deadline of ten years is the logical effect of taking a carpet's lifespan into account. Carpets generally last ten years before needing replacement (Intlekofer, 2009; Minne & Crittenden, 2015). The 2030 deadline was set in order to prevent the primary focus shifting to the production of more easily recyclable carpets, thus neglecting all carpets currently produced and those awaiting recycling. This means that within ten years a full recycling operation must be established, regardless of the carpet its material composition. If the industry is able to achieve this prior to 2030, more time will be available to device measures that meet the 2050 governmental standard. In addition, the 2030 ultimatum is in accordance with the aim of Tarkett/Desso for achieving full circularity (Tarkett, 2015, January). This is considered a verification that the industry also considers this an achievable time span.

2.4 CORE CONCEPTS

This study uses a few established concepts, framework and otherwise bodies of knowledge. These are described as "core concepts" and are part of the foundation this study is based on. These core concepts are all explained in appendix B. In this chapter only these concepts are listed. The source, which explains the concept, is not necessarily also the inventor of the concept.

The commonly used concepts are reverse logistics (cline et al., 2015); closed-loop production/circularity (Modak, Modak, Panda & Sana, 2018); supply chain management (Ludema, 2008, October); resource leaks (Olthaar, Kral & Lunenborg, 2017, October).

Full documentation of these core concepts, amongst the research frameworks that are applied, and theoretical concepts can be found in appendix B.

2.5 METHODOLOGY

This research adapts a multitude of methods, from quantitative to qualitative, in order to accomplish the objectives of this study. Although the main research question is design orientated, not all methods applied are typically used in design challenges. This provides a unique and new insight into the supply chain of the carpet industry, something which is not achieved in the current literature.

2.5.1 Mixed methods research composition

The mixed-methods research approach is one of the unique features of this study, forming a clear distinction between this study and for instance a specified lifecycle analysis or economic assessment. In order to have a scientific solid product, this research should be (amongst other criteria) replicable by other researchers. For this purpose, this section describes the methodologies as applied per sub-question. It also discusses the tools used in these methods, which are not to be mistaken for methods. The following table (Table 1) provides a schematic and easy to refer to overview of the used methods.

Table 1
Overview of the methodologies

Sub-question	Methodology	Tools
1. ***What is the logistical path of one unit of carpet tile, from production to EOL (cradle-to-grave)?***	Literature study, case study, semi-structured interviews with the industry	
2. ***What are the environmental costs of one unit of carpet tile, and how much energy is required by the logistical chain?***	Literature study for identifying key figures, modeling study, imitation experiments, expert-validation.	To create the computational model, Excel will be used.
3. ***What options are available to establish a sustainable supply chain?***	Literature study, case study, creative thinking	
4. ***What is the effect of reverse logistics on the supply chain, and how can this be used to improve the sustainability?***	Modeling study, imitation experiments, scenario analysis	
5. ***What are the success and failure factors to a sustainable supply chain, what policy is required to guarantee its success, and is governmental intervention needed?***	Scenario analysis, multi-criteria analysis, policy analysis, semi-structured interviews, expert-validation	Score-cards, analogies

2.5.2 Model construction

It is identified that this study will construct and use a model in order to calculate environmental effects. These effects will furthermore be evaluated on likelihood of adaptation through multi-criteria analyses in sub-question 5. These two steps heavily rely on data to represent the actual system as closely as possible.

The computational model is created through a process of quantifying a qualitative model. Through the conducted literature review, and a further expansion of this review in chapter 3, a graphical display of the supply chain is created. This is the conceptual model in terms of the Dym et al. (2004) methodology. Based on the knowledge acquired in the creation of this model, some modeling relationships are identified. These modeling relationships result in subsystems. With all subsystems and relationships mapped, through a system diagram, a full overview of the interdependencies of the system is presented. Finally, these interdependencies are quantified through the usage of key figures. These key figures are derived from the literature and primarily represent national figures. These figures are used to calculate the effects of the different subsystems and are used to process the modeling input following predetermined computational rules. What results is a quantified model that processes specified input measures into output factors. Validation on these results is required in order to conclude if the model behaves realistically. This validation is further discussed in chapter 6, and uses expert validation and a comparison with known emission factors of an equal system.

2.5.3 Multi-criteria analysis

Equal to the data required to create the computational model, this study also requires data for the creation of the multi-criteria analysis (MCA). This MCA is used to determine the likelihood of adaptation by the industry of the suggested measures. The results of this MCA dictate if a sustainability increasing measure is worth advising to the industry, or if it would fail certain requirements by the industry. These requirements are partially derived from the list of modeling requirements that are discussed previously and are part of the model establishment. However, some criteria are not included in the model but are regardless vital to the acceptance of technology. These criteria are primarily factors that are unrelated to sustainability in the environmental sense of the word: people and planet issues are covered by the model, the mainly economic aspects are covered by the MCA. These criteria originate from the industry themselves, as they are the end-used of the innovation. Official industry annual reports were found to be an excellent source for these MCA criteria, as these clearly state the internal evaluation criteria of the industry. As a result of this industrial implementation focus, the MCA features more criteria based on corporate continuity and financial stability rather than sustainability criteria. This is not troublesome as it is a realistic representation of the industry. Equally, the alternatives rated in the MCA are the result of design criteria which are specifically formulated to increase sustainability. So any alternative that is rated by the MCA improves the sustainability of the industry by some levels. These levels are included in the evaluation of the most likely implemented scenario.

2.5.4 Legitimizations and limitations of the methods

The mixed research method combines 9 different methodologies, making the list of limitations and constraints to these methods extensive, as is the complete legitimization of these methodologies. As most of these methods are universal and widely adapted, it was opted not to specify all legitimizations and limitations here. Instead this section is focused on specific limitations that occur when adapting the methodology to this particular study.

In expert-validation through semi-structured interviews lies a big risk. There are interview ethics that come into play, a discourse, and an evaluation environment. Only three experts are consulted for the validity testing, which are researchers from the United States and a Dutch representative of the industry. Although the American scientists have established themselves as experts on the field of carpet recycling, the discourse in the United States might be different from that of the Netherlands, thus offering different views on some constructs. Luckily the primary considered industries (Tarkett and Interface) are both of American origin, so the discourse of the experts matches the discourse in which these companies formulate policy. Having two experts is a limited pool for validity testing, which poses a limitation. Ideally, this pool of experts should be bigger and more diverse. Unfortunately, due to the COVID-pandemic, it was found very difficult to get researchers to validate the findings. Finally, there is a danger in establishing someone as an expert. Real care is required not to pressure these experts in validating the results. Likewise, great care is required in order to prevent these experts giving socially desirable answers. The experts were consulted once the model and other aspects were fully completed. They were asked to look at the modeling results, given a set of parameters, and asked if these results are in a range of what they deem likely. They were also asked which effects they miss or if they see any shortcomings. After answering these questions, their general feedback is requested. This semi-structured setup is assumed to limit the interpretation space of the expert, giving clear directions of what is expected to be validated and in which form.

2.5.5 Data sources

A cooperation was sought with Interface, Tarkett/Desso and the branch organization Modint. Due to the COVID-19 pandemic, no full-time cooperation could be established with any of these organizations. This unfortunately caused much of the gathered information from the industry to be received through unstructured, ad-hoc, interviews subject to the dangers as discussed in the previous section. This study attempted to confirm all narrative statements through established literature. In many cases this attempt was successful. In rare occasions this study will refer to a personal communication. For the modelling study of this thesis a lot of key figures were sought within official governmental sources or by highly reputable sources, all specified to the Dutch or European market.

2.5.6 Expert interviews

As Shavelson et al. (2003) identified, design studies in particular heavily rely on narrative accounts. Corporate secrecy proved to be a limiting factor in finding scientific sources, so some interviews were conducted with industry representatives to gain much needed insights. These interviews were primarily aimed at result validation and were thus semi-structured. These interviews were primarily conducted in writing through emails. The validation interview with Interface was recorded and no transcript was made per the request of the interviewee. The recordings will be kept until the public defense of this thesis. In the validation interviews, the interviewee was presented with some of the findings by this study, and was asked if these results were logical, in accordance to what they expected and if they noticed anything odd/missing from the findings. The expert was then asked to provide general (unstructured) feedback on the topic.

2.6 RESEARCH DELIVERABLES

The main deliverable of this thesis consists of three aspects. The first aspect that considered a deliverable is the model. Initially designed to be an internal tool, the model has proven to be highly capable of accurately modeling different scenarios and logistic changes. And with unknown (scientific) estimates of the current logistical costs of a carpet tile's cradle-to-grave cycle, both the academic world and the carpet industries could benefit from having this modeling tool. This paper serves as a guide to the model for academics, the industry will be sent a copy of the model with a small how-to-use guide.

The second aspect is an overview of the identified means to increase the sustainability by the carpet industry and those allied to it. Through the model, estimates of the effects are presented. Through the usage of a morphological chart, means are combined in order to form a package of tailor made alternatives (Smith, 2007). The effects of these alternatives are also included.

The third aspect is the constructed rating scheme and policy advice. The generated solutions are evaluated on criteria by the involved parties. Through a score-card setting, the different solutions are rated and presented. This is combined with a policy analysis and recommendations on governmental intervention.

All the above stated aspects form a single framework. This framework entails the creation and application of a model, ways to calculate the effects of policy measures and ways to score these policy measures. This framework results in a policy advice to the industry and government on suitability increasing measure implementation. The framework could be adopted by other researchers and be used to generate new alternatives as technology advances, and possibly even for other industries.

2.7 RESEARCH FLOW DIAGRAM

In the following paragraph, a research flow diagram is presented. This graphical display of the research process summarizes the paths to reaching a conclusion on the primary research question. The steps in the graph resemble the sub questions as discussed in chapter 2.3.

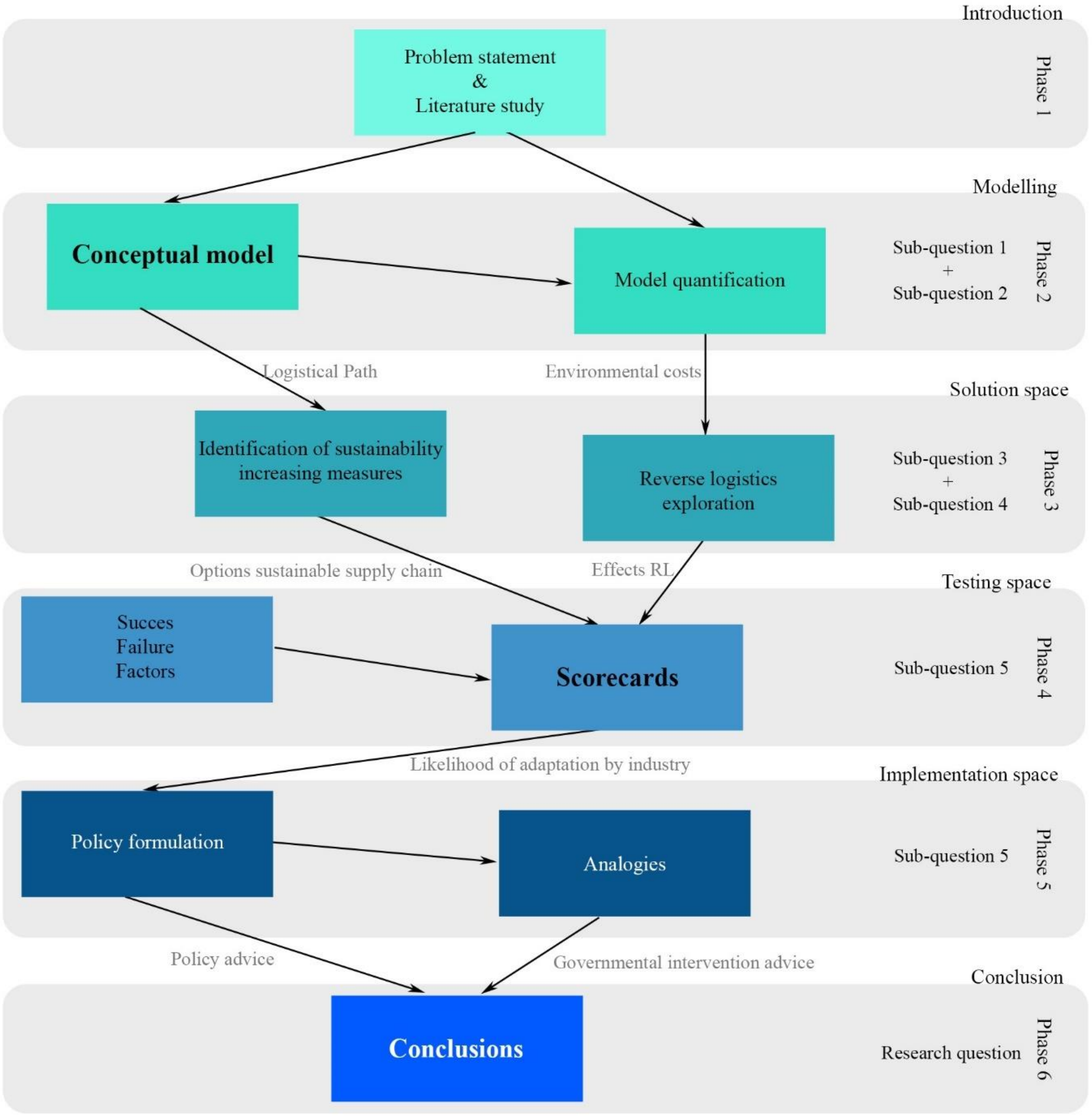


Figure 1. Research Flow Diagram

3 PROBLEM ANALYSIS

Structure

This chapter explores the issues and limitations of the carpet industry in search of why sustainable carpet production is not yet achieved. This is approached through the framework as presented by Cline et al. (2013). Section 3.1 discusses the "What", and discusses the characteristics of carpets and a carpet tile. Section 3.2 treats the "How", and focusses primarily on the production method. Section 3.3 discusses the spatial setting of the system in the "Where" factor. Section 3.4 continues with the "Who", providing a small actor overview. Section 3.5, the "Why", concludes the suggested framework by examining why carpets are so difficult to recycle. Section 3.6 creates awareness of the current stance and efforts by the industry and all involved. Section 3.7 provides a graphical display of the identified system and section 3.8 is a small conclusion on the findings of this chapter.

This chapter explores the full cradle-to-grave lifecycle of a carpet tile: from the production of a carpet tile to the end-of-lifecycle and everything in between. This is to establish clear insights in the current supply chain, which will benefit the generation of alternatives. For this exploration, the framework as suggested by Cline et al. (2013) is used. This framework applies five simple questions to examine a (reverse) supply chain: What, How, Where, Who and Why.

3.1 WHAT IS A CARPET?

Carpet is a collection name of woven fabric that is primarily used to cover floors. Carpets are often created using wool or synthetic polymer fibers such as nylon 6 or nylon 6,6. Yarn is woven to a sheet of material in a process known as tufting. In this tufting processes, loops of yarn are formed that are also referred to as the face fibers of the carpet, or "pile".

Carpet is known for its properties like providing heat insulation, noise reduction, increased comfort and simply for being decorative. Carpet manufacturers in the Netherlands produce an annual 180 million square meters of carpet, 85% of which is exported, ranking in the top five of biggest carpet manufacturing countries (Koppert & Römgens, 2012, p.4).

3.1.1 Differences between regular carpet and carpet tiles

Traditionally, carpets come either in rug sizes or are in so-called wall-to-wall units. Wall-to-wall carpets are sold per running meter (usually 4, 6 or 8 m in width) and varying in length. Fitting wall-to-wall carpets can be challenging as it requires the full (bulky) carpet to be trimmed to fit. Carpet tiles are pieces of carpet that are cut to standard units, usually 0.5 m x 0.5 m. This means that carpet tiles are more easily transported, handled and installed. With the added benefit of being modular, carpet tiles can be spot-changed. Damaged tiles can simply be replaced instead of replacing the full carpet. Furthermore, carpet tiles produce less waste, as for instance half-cut tiles can be reused in other areas of the room (Miraftab et al., 1998). Another benefit of carpet tiles, compared to wall-to-wall carpet, is a decrease of adhesives used during the application of carpet to the floor (Lampikoski, 2012). In terms of structural integrity, a wall-to-wall carpet has the benefit. These carpets are generally speaking also more durable (McDonald, 2000).

3.1.2 Carpet backing and sustainability issues

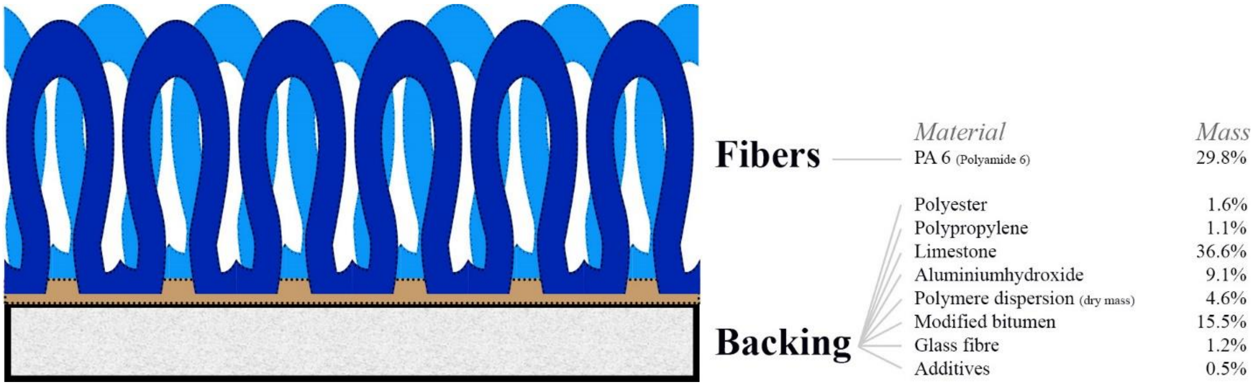
A carpet tile consists of three layers. These are the face fibers, the primary backing and the secondary backing. The face fibers are the woven yarn as discussed. This is what you can see and feel on a carpet. The primary backing material is often made from polyester or jute and forms a layer through which the fibers are woven. The secondary backing material is more complex. It typically consists of a mixture of materials that give a carpet strength and stability as well as provide a dampening effect and offer heat-resistance (Li, 2007).

Wall-to-wall carpets require the installation of separate secondary backing layer. The installation of these carpets involves a “double glue method”, in which the carpet is glued onto the secondary backing which is glued onto the floor. For carpet tiles, the secondary backing material is an integral part of the carpet. This offers a gain in durability while simultaneously decreasing the costs of installing compared to carpet tiles without a backing layer. But it also poses a limitation to the EOL stage of a carpet. Secondary backing material is known for using notoriously hard to recycle resources like Bitumen, PVC or latex. The valuable nylon fibers, which are relatively easily recyclable, are in carpet tiles contaminated with this backing material, decreasing its value substantially (Shuttleworth, Clark, Mantle & Stansfield, 2010).

3.1.3 Standard unit of carpet tile as considered by this study

Carpet tiles are a heterogeneous product: every manufacturer produces their carpet tiles slightly differently and even manufacturers have a different production method for different models of carpets. There can thus be no speak of “a carpet tile” without making a distinction what exactly the composition of this tile is. For this research the carpet tile as depicted in figure 2, based on Interface’s bestselling Touch & Tones 103 carpet tile, will be considered the standard. The assumptions and reason behind this can be found in appendix C.1.

The backing of the carpet is a multi-layered composition of different materials, ensuring the fibers stay in place, while causing additional benefits like (acoustic)dampening, (moisture) isolation and dimensional stability. In this case, for Interface’s Touch & Tones 103, this backing material consists of limestone, bitumen, glass fiber and various types of polymers. The top layer is formed out of pure nylon 6, which is created through an extrusion process. Figure 2 gives a cross-section of a carpet, in which the tufted pile and backing can be observed.



Material	Mass
PA 6 (Polyamide 6)	29.8%
Polyester	1.6%
Polypropylene	1.1%
Limestone	36.6%
Aluminiumhydroxide	9.1%
Polymere dispersion (dry mass)	4.6%
Modified bitumen	15.5%
Glass fibre	1.2%
Additives	0.5%

Figure 2. Carpet cross-section and material specification.

3.2 HOW IS A CARPET TILE CREATED?

To identify recycling methods for carpet tiles, the research should first explore how a carpet is manufactured. This serves as the foundation of the search to find sustainability increasing measures. This section discusses how a carpet is created, from the production of resources to the final assembly.

3.2.1 Carpet manufacturing process

The first step to carpet manufacturing is the creation of the face fiber. Nylon yam is treated and tufted to a primary backing layer to create a top layer. After this top layer is constructed, it is attached to the secondary backing layer. Figure 2 describes this backing layer. Figure 3 is an adaptation of the findings by Li (2007) and reflects the manufacturing phases of a carpet tile, including the energy requirement.

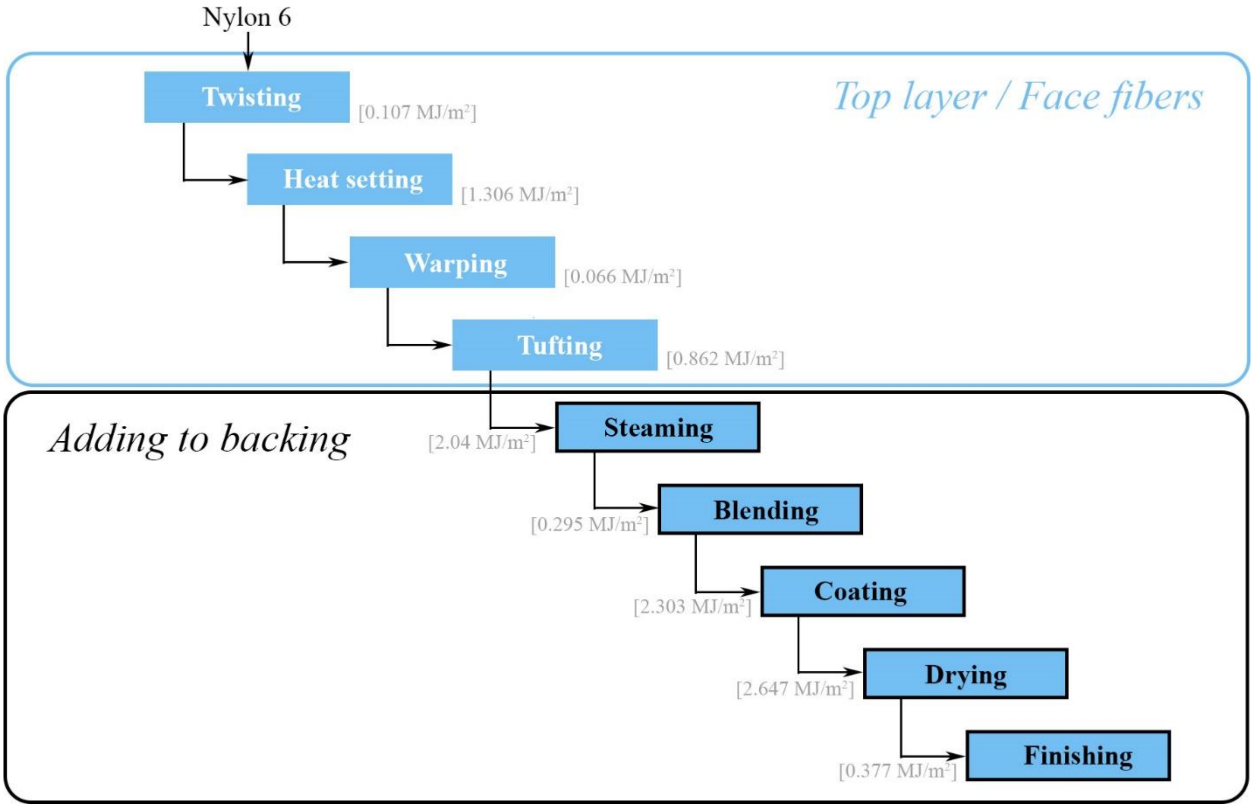


Figure 3. Production process and energy requirement.

The total energy requirement for the production of one carpet tile is slightly over 2.5 MJ per carpet tile. This fabrication method is found to be universal, although the energy requirement and procedures might (slightly) differentiate for different carpet manufacturing processes.

Just like wall-to-wall carpets, carpet tiles start off as long sheets of carpet. These are cut to size to form carpet tiles. This size can be different for manufacturers and per type of carpet. Within Europe, the standard dimension of a carpet tile is 0.5 m in length and 0.5 m in width. Inherently to this cutting, waste is created, also known as trimmings. Trimmings are estimated to be 1% of the carpet tile's total weight (based on findings by Miraftab et al., 1998).

3.2.2 Nylon coloring process

Nylon-6 starts off as Caprolactam, a chemical organic compound that is used in the production of Nylon. Through an extrusion process the Caprolactam is heated, polymerized and spooled to form nylon yarn. The coloring of nylon happens during the extrusion process of the Caprolactam. Caprolactam is supplied in a powdered form and during this extrusion, pigments are added to color the newly created nylon strands (Sitnik, Bykova & Andronova, 1988). This creates solution-dyed carpet, meaning the nylon itself is colored, not just the outer shell. The costs of this coloring were discovered to be 2.7 MJ/kg nylon 6 (Li, 2007).

3.2.3 Carpet tile material composition

As discussed, the standard unit of carpet tile is based on Touch & Tones 103 by Interface. The following materials are used in the production of this carpet tile:

Table 2

Carpet tile material requirement and purpose specification

Resource	Use
Polyamide 6	Face fibers
Polyester	Primary backing
Polypropylene	Secondary backing (Durability, stain resistance)
Limestone	Secondary backing (filler)
Aluminum hydroxide	Secondary backing (Fire detergent)
Polymer dispersion	Secondary backing (adhesion)
Modified bitumen	Secondary backing (Dimensional stability)
Glass fiber	Secondary backing (Insulator, stabilizer)

3.2.4 Origins of production resources

The resources as discussed in table 2 can be obtained through three global channels. These channels are virgin resources, downcycled resources and (closed-loop) recycled resources. The Touch & Tones 103 tile is produced out of 100% virgin resources. Some carpets by Interface feature downcycled nylon which is recovered from EOL fishing nets through the “Net-Works” program (Khoo, 2018), which will be discussed later.

The (environmental) costs of virgin resources is equal by the costs of mining these materials. The costs of downcycled and recycled resources is determined by the costs of repurposing these materials. Inspection of Interface’s Net-Works program resulted in the concluded that these fishing nets originate primarily from the Philippines, are processed in Slovenia, and are supplied to Interface Scherpenzeel as colored nylon 6 yarn through Italy (Khoo, 2018). This logistical operation spans well over 18,000 km. This indicates the need to incorporate another aspect into the analysis of the supply chain: location. This is covered in the "where" aspect.

3.3 WHERE ARE DUTCH CARPET TILES MANUFACTURED, USED, AND PROCESSED?

Cline et al. (2013) identified that an increase in sustainability can be achieved through optimizing the reverse logistics process. In this process, the (geographical) locations of the client and the place of origin are indicative. This section discusses where carpets are shipped to and from.

3.3.1 Primary Dutch carpet tile production facilities

The Netherlands hosts a few global-leading carpet tile production facilities (as discussed in chapter 2.4). This thesis considers two: Tarkett/Desso in Waalwijk and Interface in Scherpenzeel. Consumers cannot purchase carpet directly at either Tarkett/Desso or Interface but can purchase carpets through designated outlets. These outlets include various construction markets, carpet specialists and other construction/interior companies across the entire Netherlands.

3.3.2 Service range and reverse logistics policy

Carpet manufacturers have a wide network of outlets all across the Netherlands (and far beyond). The Utilitarian theory dictates that, in case of equal quality products, each manufacturer only supplies the customers closest to them. Within the Netherlands, this means the service ranges of each carpet manufacturer can be projected onto a map. The following figure, figure 4, displays this projection. In this map, red signifies the service range of Interface (Scherpenzeel) and blue marks where Tarkett/Desso is located (Waalwijk). The line indicates the exact middle of which the distance to either factory is equal. The projection indicates a maximum service range of 176 km for Interface, 117 km for Tarkett/Desso. Assuming the maximum required transportation distance, this makes for the maximum average transportation distance of (176 / 2) = 88 km.

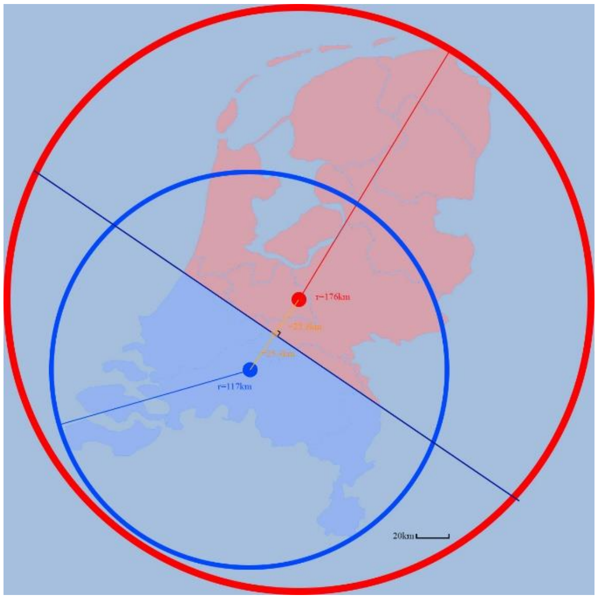


Figure 4. Service-range indication Tarkett/Desso (blue) and Interface (red)

In terms of reverse logistics, carpet manufacturers have taken it upon themselves to collect EOL carpet tiles. Both Interface and Tarkett/Desso are currently reclaiming carpets directly from their clients in aims of recycling (Deutsche Umwelthilfe, 2017, February; Vogels, 2019; E. Oudenbroek, personal communication, Feb 17, 2020). Carpets that are sold via the diverse outlets are hard to keep track of and are not collected by the manufacturers. This seemingly random reclamation of carpets begs the question: who is involved in this recollection process? This leads to the fourth identified question.

3.4 WHO IS INVOLVED IN THE CRADLE-TO-GRAVE CYCLE OF A CARPET TILE?

In order to assess the efficiency of a sustainability increasing measure, an overview of all actors that are involved in the supply chain is created. This chapter aims to briefly identify the involved parties in the cradle-to-grave process of a carpet tile.

3.4.1 Production process

Sub-contractors supply the production facilities with raw resources. The exact origins of these materials are covered in corporate secrecy. For Interface, it is known to be a nylon supplier from Italy. It is also known that the carpet manufacturing plants use spooled nylon 6, meaning that the extrusion of Caprolactam takes place elsewhere (Luqmani, Leach & Jesson, 2017). This makes for a second general party involved in the production process: the manufacturer of Nylon 6.

3.4.2 Shipping process and reverse logistics process

Interface and Tarkett/Desso are wholesalers, limiting their service range to outlets and commercial parties. For the transportation to clients and outlets they rely on a vast fleet of trucks (Deutsche Umwelthilfe, 2017, February). As 85% of the carpets manufactured in the Netherlands are exported, this fleet is larger than the demarcation of this topic might make it seem. In large/long distance shipments, external trucks (and truckers) can be hired. This makes for the shipping division to be included in the actor overview. Transshipment does occur in the loading and offloading of, for instance, trucks. This study however does assume this to be done by the same party as the shipping party.

3.4.3 Clients/Users

When a carpet is purchased, the ownership of this carpet tile shifts from the manufacturer to the customer. This customer is either the outlet or wholesaler (resell point), installation company and/or finally the client. Interface and Tarkett/Desso do not employ installation technicians themselves. For contracted jobs, carpets are mostly just delivered to the site and the contractor will take care of the installation.

3.4.4 EOL processing

Private citizens can dispose their EOL carpets at recycling plants. Within these governmental recycling plants, carpets are categorized as fabric waste. Fabric waste is a high value product and is sent to a sorting center. At this facility, workers inspect the fabrics for reuse: either reuse as garments, as cloths, or as valueless waste. Carpet is structurally considered waste and is shipped back to the recycling plant for disposal (de Kok & van den Acker, 2019, march). A highly inefficient policy.

For larger quantities of carpets (industrial quantities) or carpets with a commercial usage, the government requires specialized industrial waste disposal. This is often a contracted service with specialized waste disposal companies. The carpets are directly disposed of instead of first being sorted at the recycling station.

Three types of uses have been identified for EOL carpets. Closed-loop recycling is the optimal scenario, in which EOL carpets are fully used to produce new carpets. This was deemed unachievable by, and for, the industry (Helms & Hervani, 2006). The second option is downcycling. Downcycling requires a market for the EOL product, which is currently not established. This only leaves the disposal method. In the literature, two main types of waste disposal have been identified. These are landfilling, the current default for Dutch carpet waste, and incineration (with energy regeneration).

3.4.5 Governmental and sector association

The carpet industry is unionized and represented by two organizations. These are branch organization MODINT and “Verenidgde Nederlandse Tapijtfabrikanten”. Between these two representatives and the government, a multi-year plan was formed to increase the energy efficiency of the carpet industry (Koppert & Römgens, 2012). This confirms that the government has an invested interest in the carpet industry and increasing their sustainability.

3.4.6 Overview of actors

The previous chapter discusses the current status of the industry and briefly touches upon all that are included in the supply chain. These actors are again listed in this overview. Through this overview of actors, it is emphasized that there are multiple actors involved in the supply chain. Although it was identified that the industry and the government have the highest invested interest and power, failing to consider or include any of these other actors might prove to be an obstacle when implementing any changes to the policy. These actors might have conflicting interests and could hinder continuity of operation. In the following overview, general applicable goals like profit maximization are not included.

This overview is not, in any way, presented as a full actor analysis or as a source for the establishment of a complete supply chain analysis. It is merely a summary of what has been previously concluded. Corporate secrecy make it hard to determine exact actors as well as their logistical processes. This is a limitation to the analysis and general study, and as such will be discussed in chapter 8.4.

Table 3
Actor overview

Where in the supply chain?	Actor	Main interest	Source
Production	Resource suppliers & sub-manufacturers	Ensuring stable supply of good quality	Luqmani, Leach & Jesson, 2017
Shipping	Trucking companies	Minimize transportation risks	Deutsche Umwelthilfe, 2017, February.
Clients	Retail points, resellers and installation companies	Provide customer service, reach wider market, decrease nuisance and inconvenience of customer	Blanco & Fransoo, 2013
	Client	Durable product, minimal nuisance	Mostafa, Batool & Parvaneh, 2013
Waste sorting & processing	Recycling center & fabric sorting station	Highly recyclable product, high sorting speed, low refusal rate	de Kok & van den Acker, 2019, March.
	Landfill site (govt./private)	Landfill only valueless products	Koppert & Römgens, 2012
	Waste incineration plant (govt./private)	Safety, stable energy production	G. Sterk, personal communication, august 14, 2020

3.5 WHY DO CARPETS POSE A BIG ENVIRONMENTAL STRAIN AT EOL?

Efforts by the industry seem to indicate an effort to adapting a circular economy model. However, the findings of Miraftab et al. (1998), Cline et al. (2015), RoyalHasoningDHV (2017, November) and the Dutch ministry of Infrastructure and waterways (Ministerie van Infrastructuur en Waterstaat, 2019, July) dispute this: carpet tiles are still being landfilled in large quantities. This section explores the "why".

3.5.1 Problematic material composition and production

Carpets and carpet tiles are very difficult to recycle (Choudhury, 2014). The adhesion of nylon fibers to the backing material is one of the main issues (Shuttleworth et al., 2010). Adding to the problematic EOL is the bitumen backing. Bitumen is a raw oil product and, once mixed with resources like limestone and glass fiber, cannot be repurposed in the current production setup (Shuttleworth et al., 2010). With that, the economic costs of bitumen created from virgin resources is relatively low, making it more financially viable to acquire new bitumen rather than reclaiming it from EOL carpet (McNally, 2011). The separation of top layer from the backing layer is relatively easily achieved, but the economic costs of recycling is simply outweighed by the costs of virgin resources (Li, 2007; E. Oudenbroek, personal communication, Nov 02, 2020; Schmidt & Cieślak, 2008).

3.5.2 Lack of alternative disposal methods

As far as disposal measures go, landfilling is not the only option. Carpet tiles could theoretically be used as fuel for incineration plants. Incineration plants offer waste disposal with the added benefit of regeneration of heat and electricity. However, there is little to no scientific evidence that energy regeneration through incineration of carpets is a disposal method available in the Netherlands. A more extensive inquiry into this fact at different waste treatment facilities led to the discovery that the Dutch incineration facilities are unfit to treat industrial quantities of carpet (G. Sterk, personal communication, august 14, 2020; M. De Jong, personal communication, august 18, 2020; T. Van Winden, T., personal communication, august 31, 2020). This is primarily due to the fact that carpets have a higher caloric value than common household waste. Dutch waste treatment plants are designed on an average caloric value of mixed household waste at 10 MJ (Arkenbout, 2019). Carpets create upwards of 20 MJ of energy per incinerated kilogram, twice the energy the incineration plant is designed to operate on (De Jong, M., personal communication, august 18, 2020). Simply put, carpets are refused from incineration since they burn too hot compared to common household waste (Helftewes, Flamme & Nelles, 2012)

3.5.3 Lack of EOL-product market

One way to prevent carpets hitting the disposal phase altogether is through recycling or downcycling. Interface identified that recycling is economically impossible with the current manufacturing processes and material composition (E. Oudenbroek, personal communication, Feb 17, 2020). This makes downcycling the only alternative. In order to establish an effective downcycling method, a market is to be created, generating a demand for the downcycled resources that once formed a carpet tile. As discussed in the literature study (Chapter 2.2), FRC was identified to be one of the very few uses for downcycled carpet tiles. However, as FRC only uses the nylon fibers, all other material (roughly two-thirds of the entire carpet tile's weight) still requires disposal, not to mention the FRC itself at its EOL. This indicates that there needs to be a demand for recycled resources in order to divert carpets from the landfill.

3.5.4 Financial aspects of recycling and disposal of EOL carpets

The recycling and/or downcycling of materials from EOL carpets are deemed achievable, yet financially undesirable (E. Oudenbroek, personal communication, Feb 17, 2020). Meaning that the process of recycling will cost more than obtaining these resources via other sources. This caused the assumption that nylon was too expensive to be used as insulation material in homes (Alam, Singh & Limbachiya, 2011). The same goes for Bitumen. It was identified to be a relatively intensive and complex process to separate the bitumen from all other backing material, whereas virgin bitumen is relatively cheaply acquired and readily available (McNally, 2011; E. Oudenbroek, personal communication, Nov 02, 2020). If, however, these resources are in danger of becoming scarce, or their price rises otherwise, this evaluation shifts. Currently none of the resources (or finished product) is seemingly worth the trouble of saving it from landfilling, but governmental intervention is feared by the industry (E. Oudenbroek, personal communication, Nov 02, 2020).

3.6 CURRENT STATUS OF THE INDUSTRY

Based on current findings, there seems to be a standstill in the carpet industry. EOL carpet is too expensive and too difficult to recycle, uses for downcycling are lacking, and EOL carpets are not accepted by incineration plants. Luckily industries are always evolving, and technological advances always await. It is for this reason beneficial to explore the most recent developments within the supply chain. This paragraph aims to identify the current stance of the industry, sector association and the government.

3.6.1 Stance of the industry

The environmental strain of EOL carpets has not gone unnoticed within the industry. World leaders in carpet tile manufacturing, Interface and Tarkett/Desso, have made it their business goal to either produce carpet completely CO_2 neutral by 2020 (Interface, 2019, April) or to achieve high circularity (Tarkett, 2015, January). The Condor Group, one of Europe’s biggest carpet producers, matches these goals and also states to aim for zero-waste and energy neutral carpet productions (Condor Group, 2020). Interface’s mission, called mission-zero, is aimed to produce carpets from fully sustainable and/or recycled materials, as well as having a zero carbon emission footprint on the environment (Interface, 2019, April). Tarkett is in the process of reclaiming EOL carpets and aims to achieve full circularity by 2030 (Vogels, 2019). Modeling studies indicate a shortage of processing capacity for EOL carpets by the industry itself regardless of the efficiency of the reverse logistic model (Biehl, Prater & Realff, 2007). And unfortunately, both Interface and Tarkett/Desso are left to conclude that their own goals were too optimistic (Interface, 2019, April; Vogels, 2019). As modelled by Biehl et al. (2007), and contrary to Interfaces’ mission statement, their current recycling effort is hardly what they make it seem. It is estimated that between Tarkett/Desso and Interface, about 1%-3% of all carpets produced are reclaimed (Deutsche Umwelthilfe, 2017, February). Although they have (successfully) integrated other recycling methods into their production line (mainly reusing EOL nylon fishing nets), the vast majority of returned carpets remain in storage as there is no processing capacity. Furthermore, as of 2020, the entire recycle effort was recently even cancelled for the entire Europe, Middle East and Africa (EMEA) by shutting down the recycling operations in the Scherpenzeel factory, the Netherlands (E. Oudenbroek, personal communication, Feb 17, 2020). So, although Interface appears to be very aware of the environmental impact, and despite the public image of a very responsible production method, their recycling effort hit a screeching standstill: carpet tiles are not being recycled, they are simply being moved. There is a technology pull by the sector that has gone unanswered.

3.6.2 Stance of the government and sector association in The Netherlands

Within the Netherlands governmental disposal sites are available to the public for most bulky waste products. Called "Milieustraten", these sites offer free-of-charge garbage disposal for households. End of Lifecycle carpets fall under the umbrella of 'textile' in these garbage disposal plants and recycling industry (de Kok & van den Acker, 2019, march). Effectively, this means that carpets are disposed of in one container alongside high value resources such as intact clothing. The waste collection facility ships all textile to secondhand stores for sorting and reselling (de Kok & van den Acker, 2019, march). Carpets that end up at these secondhand stores for sorting are rarely resold. They simply end up being returned to the city's garbage disposal unit, after which they will be incinerated or end up in landfills (Royal HaskoningDHV, 2017, November).

In 2012, the State Secretary for the Environment was advised on stimulating the recycling efforts of the carpet industry. In the report "Hoe kunnen we 2/3 van het huishoudelijk afval recyclen?", the State Secretary is advised to compensate the startup costs by the industry for the adaptation of recycle equipment. The analysis concluded that once these startup costs were to be mitigated, a self-sufficient recycling operation should be the result (de Baedts, 2012, may). It is mentioned that recycling of EOL carpets has a large, positive, environmental impact for the country. And while this report led to the creation of the program "VANG-HHA" (Van Afval Naar Grondsof) and was adopted by the Dutch program for Circular Economy (2016), the advice of financial stimulation to cover recycling startup costs have not made its way into policy. Current policy (2019) regarding the recycling efforts of carpets is a far cry from that what was once envisioned: Carpets are to be averted from disposal because they are deemed to be too valuable, with the exception of carpet tiles. Because of an often present bitumen backing, which is said to be hard to recycle, carpet tiles are on forehand destined for landfills (Ministerie van Infrastructuur en Waterstaat, 2019, July). "Insufficient recycling capacity and no market for the recycled product" was the definite verdict on carpet tiles by the ministry (Ministerie van Infrastructuur en Waterstaat, 2019, July). Not only is there no compensation for the establishment of a closed-loop production system, the Ministry acknowledges that there is no demand and takes no pre-active stance to combat this. A knowledge gap can clearly be identified within the position of the Dutch government. EOL carpets are deemed valuable by the government, yet there is no market or demand for the product and carpet tiles are thus worthless. Policy is failing. Perhaps the industry itself offers a solution.

3.6.3 Main focus increasing sustainability by the carpet industry.

In the initial search for improving sustainability of the carpet industry a wide range of (technical) solutions were discovered, mostly aimed at the production phase. This has clearly been the primary focus point of the industry for some time (E. Oudenbroek, personal communication, Feb 17, 2020). The dyeing of carpets seemed to be the number one culprit of causing environmental strain (Capar, Yetis & Yilmaz, 2006; Shaikh; 2009, Kant 2012). All literature suggests new technological processes to reduce the environmental impact of coloring fabrics such as dyeing during the extrusion process (Capar et al, 2006; Chinnasamy et al., 2010; Kant, 2012). The technology pull by the industry thus has not gone unanswered, but it is primarily focused on the coloring aspect of carpets, not the recycling.

3.6.4 Increasing circularity for the carpet industry

A recent shift in focus for the carpet tile industry was observed in trying to achieve circularity. To mitigate the environmental impact of the production of carpets, ways of dealing with leftover products are sought. A positive trend currently happening that is diverting old carpets from landfills (Cline et al., 2015), but these diverted carpets do not end up becoming new carpets (Peoples, 2006; Miraftab et al., 1998). Cline et al. (2015) continued the analysis by concluding that a good infrastructure was needed to facilitate reuse, arguing for the establishment of a reverse logistics system. With the insight that EOL carpet tiles have some degree of value, but are still being discarded in landfills, it made for a shift of focus towards the logistic value of one unit of carpet tile. Apparently there are applications for reusing carpets that remain unused due to factors unknown. This puts a heavy strain on the virgin resource acquirement as well as disposal methods, as indicated by the causal diagram (Figure5). A solution possibly lies within resource management

3.7 GRAPHICAL DISPLAYS OF THE SUPPLY CHAIN

This causal diagram displays relationships amongst the different phases in the lifecycle of a carpet tile, and is the result of the previously described findings. Positive effects, indicated by the "+" symbol, indicate a positive correlation: if i.e. more carpet tiles are produced, more transportation effort is required to supply the customer with this product. In a similar fashion, the negative relationship (indicated with the

"-" symbol) represents an inverted relationship. When more product is recycled, less raw material is required to be produced.

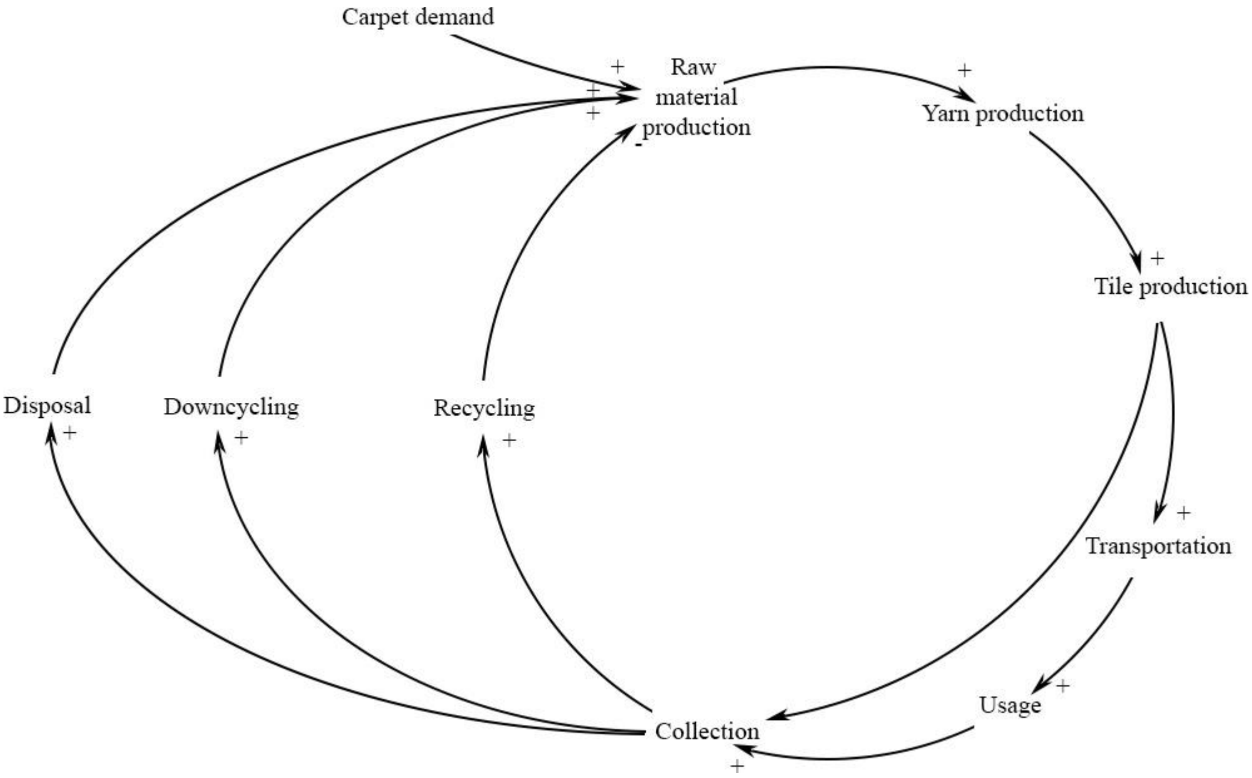


Figure 5. Causal diagram of the identified system and possibilities.

Within this causal diagram, three circles have been identified. These go from least- to most preferred in terms of environmental strain on exhaustible resources. The widest circle includes disposal options, meaning the EOL carpet ends up landfilled or incinerated. The middle loop flow is the downcycling flow, in which the EOL carpets are used for other industries. The flow that forms a perfect circle is the recycling flow, in which EOL carpets are used to create new carpets. This is the circularity alternative, limiting the requirement for virgin resources.

Both Interface and Tarkett/Desso are now in the process of reclaiming used carpets in order to achieve circularity, but these efforts are still anything but successful (Deutsche Umwelthilfe, 2017, February; Vogels, 2019). Information obtained from the vice president operations of Interface even indicates that the reclaimed carpets at Interface are being stored all over Europe, the Middle East and Africa (EMEA) as there is no clear policy for reverse logistics and hardly to no processing power for recycling (E. Oudenbroek, personal communication, Feb 17, 2020).

Using the causal diagram, and the analysis of the current situation as described by the previous sections, a display of the current supply chain is formulated. As it stands currently, the following supply chain is realized:

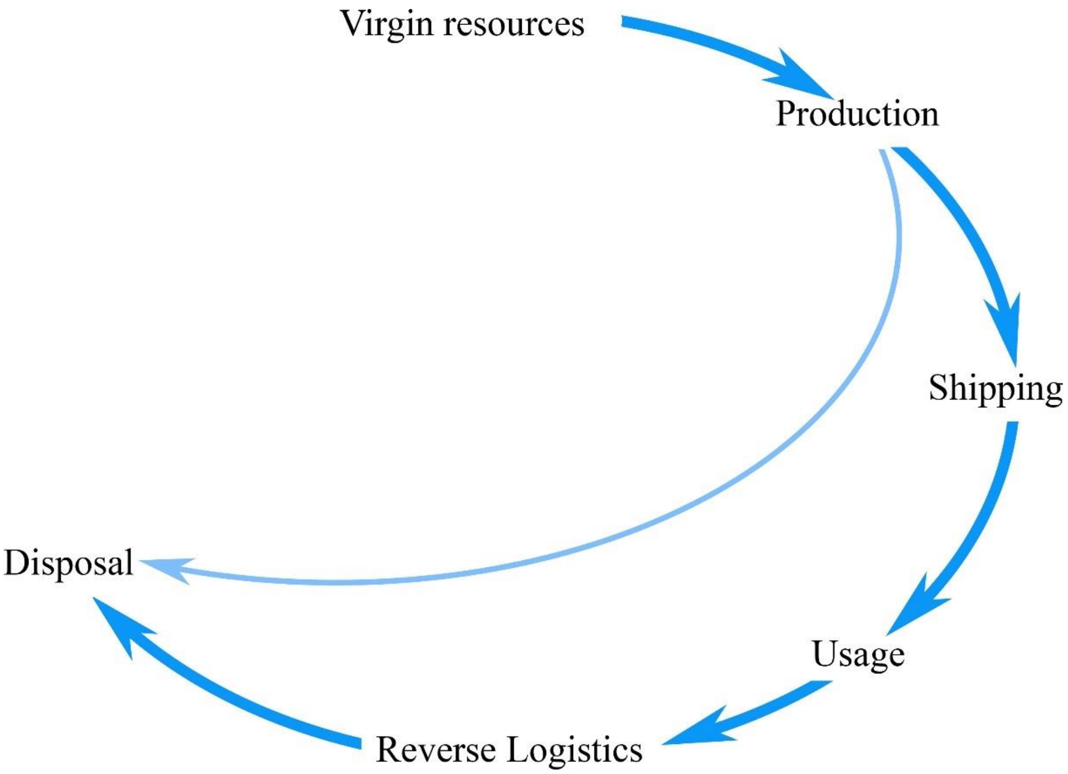


Figure 6. Representation of current logistical chain.

As observed in the model the supply chain is not closed, meaning there is no return flow of goods towards the production facility in terms of reusable resources. The current production process fully relies on virgin resources and disposes the carpets at its end of lifecycle (Deutsche Umwelthilfe, 2017; Bossenmayer, Peters & Schindler, 2019). This is nowhere close to the industry set goal of achieving full circularity. The next chapter discusses the development of a computational model to calculate the environmental costs of this failing policy and which is used to generate sustainability increasing measures.

3.8 FAILURES OF THE SUPPLY CHAIN

Somewhere in the chain, carpets lose their value for being recycled into new carpets. This results in the fact that only 1% of all carpets are being recycled (Helms & Hervani, 2006). Experts indicate that a well-established reverse logistic process is necessary to prevent his devaluation of EOL carpets (Fleischmann, 2003; Cline et al., 2015). Closed loop production theory was identified as a great tool to ensure sustainability, service and economic gains (Winkler, 2011; Sharma, Panda, Mahapatra & sahu, 2011;

Kinobe, Gebresenbet, Niwagaba & Vinnerås, 2015). This however does not translate to the observed lack of demand for used carpets (Helms & Hervani, 2006). A well setup (logistical) infrastructure will aid the effort of reusing carpets (Cline et al., 2015) but is currently only one of the failing factors (Helms & Hervani, 2006; Realff, Ammons & Newton, 1999; Biehl et al., 2007). There is simply not enough value in an EOL carpet that make it worth recycling.

Problem analysis conclusion:

Carpet tiles are of complex material composition. This makes recycling and downcycling efforts complex and costly. For the current Dutch supply chain, these recycling and downcycling processes are thus not observed. A lack of recycling possibilities, limited availability of (effective) downcycling possibilities and no alternative disposal methods make for carpet to be destined to the landfill. There is a technology pull by the government and industry, actively seeking technology to increase the sustainability of the carpet supply chain.

4 MODEL DEVELOPMENT

Structure

This chapter describes the establishment of the model. This is done through discussing the conceptual design of the model in section 4.1. Section 4.2 continues to list the requirements: the what the model should and should not be capable of doing, through a detailed MoSCoW list. Section 4.3 presents the detailed design, specifying some of the key data used. Section 4.4 continues to present the sub-processes that describe the functionality of the model. Section 4.5 describes how the model can be used, and section 4.6 presents the calculated emissions of the current supply chain.

This chapter discusses the functionality of the model in greater detail. It describes how the model is created through the formulation of requirements and functionality. It also lists what key figures are used to establish the computations of model. As for all scientific research, the model should be replicable by other researchers. For this purpose, the chapter also provides a system diagram, to represent the calculations made by the model.

4.1 CONCEPTUAL MODEL

Chapter 3 discusses the current supply chain of the Dutch carpet industry. In this chapter some processes are hinted at that could aid the establishment of a sustainable supply chain. To explore these opportunities, they are adapted into a conceptual model that will form the basis of the computational model. Figure 7 presents this conceptual model. It is standardized to one unit carpet tile (0.25 m^2) of Interface's Touch & Tones 103 carpet. The conceptual design represents resource flows in a situation of recycling, downcycling, and disposal/virgin resources. The color marks the desirability in terms of circularity, not in terms of the multi-facet sustainability (green is optimal desirability, red is least desirability).

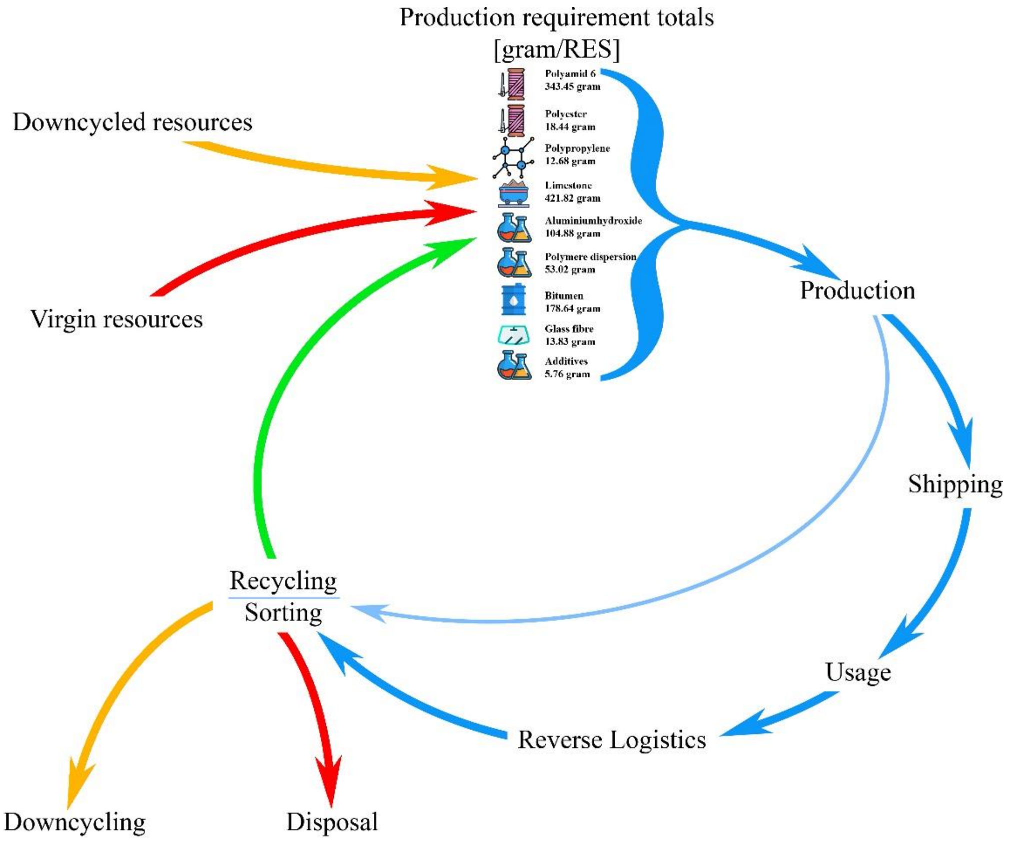


Figure 7. Full conceptual design.

The total resource requirement to produce one unit carpet tile is captioned in the function of $\Sigma P_{tot}(RES)$. The "production requirement totals" dictate the exact number of grams per material required to produce one unit of carpet tile, regardless of the origin of this resource. Resources are assumed to be pure and different sources can thus be combined to form one unit of carpet tile.

4.2 MODEL REQUIREMENTS

The establishment of the model is approached through the design philosophy of Dym et al., (2004) and will be discussed in terms of objective, constraint, function and means. This makes for a list of factors that prescribe the functionality of the model.

4.2.1 Objective

It was identified that increased sustainability can be achieved in several ways. The added benefit of the model is that the outcomes of a policy measure or technological adaptation can be simulated, reducing the uncertainty of a difficult and costly implementation. It is a gauge for the effectiveness of a sustainability increasing measure. The first objective of this model is to prove a reliable and valid quantification tool for the current situation. Only then the effect of the different sustainability increasing measures can be calculated. To achieve this, the model has to be able to turn input variables, such as material requirement, resource flows and recycling efforts into a sustainability score. This sustainability was identified as being a reliance on virgin resources, emissions, and energy requirements for the cradle-to-grave lifecycle.

By no means should this model be presented as a fully, all entailing, representation of the reality. Some aspects of the supply chain are not modelled due to different reasons and as such pose limitations to the functionality of the model. The model is no more than a static tool, a laboratory, that deals with situations that are coded into the tool on forehand.

4.2.2 Constraints

The design of the model is subject to several constraints. These constraints pose limits to the design and the outcome of this design (Dym et al., 2004). For the model, and its specific purpose of being able to quantify effects in terms of emissions, these constraints primarily come down to validation and adaptability of solutions. The following constraints were identified and are explained more elaborately in appendix C.1.

- **Model measures should be logical, explainable and within the realm of possibilities.**
  Unlikely or unrealistic modeling results and measures, like a sustainability increasing measure that causes emissions and energy requirements to increase, do not attribute towards reaching the goal of sustainability and are not adopted.
- **The model is to accurately and realistically simulate the current situation.**
  If the model cannot model the current situation correctly, any adaptation of the model will result in equally incoherent results. A validation using the manufacturers EPD is applied, the model is to produce results within a 5% deviation range of the EPD.
- **Costs of means should be in proportion to the benefits**
  Exotic sustainability increasing measures that require high capital and yield low results are excluded from consideration.
- **Implementation of means should be within 10 years**
  With the goal to increase sustainability by the year 2030, any sustainability increasing measure that is highly futuristic of nature or highly uncertain will not be considered.

A side note on the financial aspect of the means should be made. Through environmental regulations, the government is able to exercise their influence on the industry. Likewise, the government has proven to be very willing to aid the industry in increasing sustainability, even offering to compensate investment costs.

This calls for the creation of two scenarios: one in which the industry is responsible for the costs of increased sustainability, the other in which the government will finance these measures.

4.2.3 Function

The functionality of the model is described by a full list of model specifications according to the MoSCoW method. This method displays four aspects of the design: must have, should have, could have and will not have. These specifications are derived from the literature as well as from personal communications with the industry. The full list can be found in appendix C. Here, only the "must have" and "should have" functions will be displayed. Some of the functional components were found to be unknown or required assumptions. These will be discussed in appendix F.

Table 4

List of must have factors according to MoSCoW methodology.

Must have	**Source/origin**
Downcycled resources source stream	Lampikoski, 2012; Khoo, 2018
Virgin resources source stream	Cline et al., 2015
Product specification	Nelson, 2009, also based on limitations of treating carpet as homogeneous product.
Shipping stream (manufacturer to customer)	Cline et al., 2015
EOL disposal stream	Cline et al., 2015
CO_2-equivalent costs overview	Heijungs, 2005

Table 5

*List of should have factors according to MoSCoW methodology***.**

Should have	**Source/origin**
Energy source selection	DuBose, 2000
Emissions per energy source	DuBose, 2000
Closed loop recycling stream	Fleischmann, 2003; Cline et al., 2015
Reverse logistics stream	Cline et al., 2015
Recycling/downcycling specification	Helms & Hervani, 2006; Biehl et al., 2007; Choudhury, 2014
Productional losses stream	Condor Group, 2020
Selection of methods and distances for transportation	Cline et al., 2015
Energy costs overview	Choudhury, 2014
Disposal options	Choudhury, 2014; Miraftab et al., 1998
Usage losses to carpet	Condor Group, 2020
Beeline to actual kilometers shipping conversion	Bosco, Henry & Zdeb, 2012

This list gives an approximation of what should be included in the model for it to function as designed. The sustainability increasing measures are not yet presented in the MoSCoW list but are detailed in the following design step: describing the means.

4.2.4 Means

As the literature study indicated (chapter 2.2), three main areas are identified where resource leaks occur and where sustainability can be increased. These areas are portrayed in the conceptual model per chapter 4.1 and were found to be "Shipping and reverse logistics" (Cline et al., 2015, amongst others), "Production" (Realff et al., 1999, amongst others) and in "Recycling/sorting" (Helms & Hervani, 2006, amongst others). These three areas form the solution space: a categorization of means. The following table displays the solution space and the identified means in each of these areas. These means are either identified during the literature study (chapter 2.2) or through the exploration of the problem in chapter 3. The chapter in which these means are identified will be presented as well and serve as a reference.

Table 6

All identified sustainability increasing measures

Production leaks	Transportation & RL leaks	Waste treatment leaks
Implementing a zero-emission production method *Chapter 2.2*	Relocation of production facilities to decrease shipping distance *Chapter 3.3*	Incineration of EOL carpets with energy regeneration *Chapter 2.2*
Implementing a zero-waste production method *Chapter 2.2*	Implementing alternative (zero-emission) transportation means *Chapter 2.2*	Downcycling of EOL carpets through Fiber Reinforced Concrete (FRC) *Chapter 2.2*
Implementing a zero-emission recycling method *Chapter 2.2*	Decentralized collection of EOL carpets to decrease reverse logistic distance *Chapter 3.6*	Downcycling of EOL carpets through (wall) insulation material for buildings *Chapter 2.2*
Adapting a zero-emission resource policy to limit the costs of resources *Chapter 2.2*		Adapting a full circularity model *Chapter 3.6*

As many of these means are already discussed to some detail in the literature study, only a brief explanation of these means will be presented. A full explanation to these means is found in appendix D.

4.2.4.1 Means description - Production leaks

Implementing a zero-emission production method

Carpet manufacturers value renewable energy sources highly (DuBose, 2000). Means are identified to approach a zero-emission production method. This includes the usage of renewable energy sources and limiting or capturing all emissions of the manufacturing process like heat, (toxic) fumes and particulate matter.

Implementing a zero-waste production method

During the manufacturing process of a carpet tile, an estimated 1% of material is directly discarded. This is due to the carpets being cut to carpet tiles post-construction (Miraftab et al., 199). This sustainability increasing measure aims to implement new production methods that fabricate carpet tiles without waste.

Implementing a zero-emission recycling method

Like the zero-emission production method, the recycling process can also be optimized to approach zero-emissions. This requires for instance the shredding machinery (that separates the nylon top fiber from the backing material) to be fully airtight to prevent particulate matter from being released. It also assumes the usage of zero-emission, renewable, energy sources.

Adapting a zero-emission resource policy

The mining of virgin resources was found to be heavily environmentally straining (CE Delft & Rijksdienst voor Ondernemend Nederland, 2018; Hammond, Jones, Lowrie & Tse, 2008). This measure assumes the adaptation of zero-emission resources, meaning no emissions occur during the mining or production of the resources required to construct a carpet tile. This could possibly require a change of the carpet tile's composition and fabrication method.

4.2.4.2 Means description - Transportation and Reverse Logistics leaks

Relocation of production facilities

As identified in chapter 3.3, the location of the Interface and Tarkett/Desso plants is sub-optimal when looking at the supply of the Dutch market. Ideally, the Interface production factory should be moved further north to supply the northern half of the Netherlands with carpet tiles, while Desso supplies the southern half of the Netherlands. This could reduce the maximum shipping distance from 176 km beeline to 117 km beeline, a 33% reduction.

Implementing alternative (zero-emission) transportation means

Diesel combustion engines are generally known as environmentally straining, although this is topic of high controversy as of lately (Platt et al., 2017). This sustainability increasing measure assumes that the current EURO-6 classification diesel engine is replaced by either a hydrogen fuel-cell or a battery powered electric motor. The term “zero-emission” could be misleading as the combustion engine is accredited for only a small part of the total emissions of vehicular movement (Timmers & Achten, 2016). The emission of transportation will never be zero, but a reduction of emissions is observed in this possible alternative.

Decentralized collection of EOL carpets

The carpet industry’s failing RL policy indicates that the recollection of carpets by the manufacturer is currently not a viable alternative. This option explores the opportunity of disposing carpets locally at the closest (governmental operated) recycling plant. This reduces the RL distance from an average 123 km to just 10 km. This means does require policy adaptations, as it indicates a shift in responsibility of the EOL product from the carpet manufacturer to the customer/recycling plant.

4.2.4.3 *Means description - Waste treatment leaks*

Incineration with energy regeneration

Although Dutch waste incineration plants are unfit to incinerate carpet waste, the literature indicates foreign states are able to incinerate carpets (Cline et al., 2013). This sustainability increasing measure assumes adaptations of the Dutch waste incineration plants to facilitate the incineration of carpet tile waste at a 20 MJ energy regeneration rate.

Downcycling to FRC

Fiber Reinforced Concrete is widely considered to be the best purpose of downcycling for EOL carpets. From one EOL carpet tile, 15 kg of FRC can be created. However, in terms of long-term sustainability, it is disputed by this study that FRC actually increases sustainability. This study argues that FRC produces an even larger landfilling strain. At 1250 kg/m^3 volume of concrete, one EOL carpet tile produces 1.2 x10^{-2} m^3 landfilled product. FRC is still included in the measures due to the common misconception of its effect and will be further specified in appendix D.3.2.

Downcycling to insulation material

Carpets in general, and more specifically nylon, are known to insulate well (Alam et al., 2011). This measure suggests that nylon 6 fibers can replace rockwool and be used to insulate buildings. This assumption is unproven and if found to be a viable alternative, requires further research.

Adapting full circularity

The preferred alternative by the carpet industry and the government fully sustainable carpet tiles. This means that carpet tiles are entirely produced out of recycled carpet tiles. This means could thus not be excluded, even though this option was deemed unachievable in the current situation. It serves as an exploration of the possible results of a circular economy for the carpet industry.

4.3 DETAILED DESIGN

This section discusses the modeling assumptions and key figures as used by the model in greater detail. This serves to further refine the understanding of the model results, and for replication purposes. For all key figures, this chapter refers to appendix F, where all used key figures and their sources will be list-wise presented for replicability. This chapter was formulated according to the Dym et al. (2004) design methodology, and as such will be discussed as the detailed design of the model.

4.3.1 Specifications of the carpet tile

For validation purposes, this study has adapted Interface's Touch & Tones 103 carpet tile as the standard unit. Through the material specification, the material costs of producing one carpet tile can be computed in terms of Global Warming Potential (GWP) and Gross Energy Requirement (GER). GWP is presented by CO_2-equivalents units, a widely used and accepted calculation method for calculating environmental impact of GHGs (Gillingham & Stock, 2018, Cain, Lynch, Allen, Fuglestvedt, Frame & Macey, 2019). GER is represented by megajoule energy and expresses the effort of mining, creation, transportation and exhaustible resource depletion in one primary energy figure (CE Delft & Rijksdienst voor Ondernemend Nederland, 2018). It is widely used to calculate the effects of resource usage.

Unfortunately, most official Dutch sources for emissions and energy requirements, like CE Delft & Rijksdienst voor Ondernemend Nederland (2018) and the official CO_2 emission factors for fuel report (van Harmelen & Koch, 2002), fail to provide a range of likely values. Instead, they either provide the mean, median, or do not even discuss how this key figure is computed. It is up to the researcher to establish this range, which is presented as part of the validation chapter (chapter 6).

4.3.2 Production method and energy

Besides the raw material, machinery is required to produce a carpet tile. This machinery relies on electric energy to operate. This energy is expressed in megajoules per carpet tile for the individual phases of fabrication. The emissions that occur in these stages is partially dependent on the selected energy source. Some energy sources, like biomass or coal incineration, emit more GHGs and particulate matter than renewable energy sources like solar or wind energy. Although this study discusses these renewable energy sources as part of a “zero-emission” policy, they do in fact have a GWP as identified by the European Environment Agency (Nielsen, Plejdrup, Rentz, Oertel, Woodfield & Steward, 2019). This effect is included in the model.

4.3.3 Transportation

Cargo transportation emissions are often expressed in a unit of weight, being the tonkilometer (tkm). This is the required effort/produced emissions to transport one ton of metric weight over 1 km. It can thus be concluded that transportation emissions are the product of mode specific emissions, distance and weight of the transported material/cargo. For a car, tkm is rarely used as a unit and this was not found in the current literature. It was computed through a case experiment. This computation can be found in Appendix F.4.1.1 as well as the explanation as to why the car is included. The demarcation of this study assumes that all carpet is shipped through road transport. There are other modalities available, but these are deemed too costly and too inconvenient for national shipping. These modes are however included in the model for future studies that includes carpet tile exportation.

4.3.3.1 Shipping distance

As discussed in the problem analysis “where” (chapter 3.3), the average transportation distance is estimated to be 88 km single trip. A 40% beeline conversion ratio is adapted to model travel distances across roads (Boscoe et al., 2012).

4.3.3.2 Unit weight

A carpet tile weighs 1152.5 grams. The study by Bossenmayer et al. (2019, January) indicates that through the lifecycle of a carpet tile, the carpet tile loses 12% of its weight. This means that the weight for reverse logistics is 12% lower than the original transportation weight, causing a decrease in shipping emissions.

4.3.3.3 Electric GWP

The global warming potential of electric powered vehicles is topic of much discussion. Some researchers argue that a maximum savings of 43% in GWP is achieved compared to combustion engines (diesels in particular). Others argue that the GWP of these vehicles is equal. This study presents the GWP of electric vehicles in this range, but the model uses the maximum 43% savings for modeling purposes.

4.3.4 Recycling/downcycling/disposal

Figure 8 is used to represent the EOL stage of a carpet tile. It reflects the different uses for a carpet tile as identified in previous chapters and includes the specific energy requirements per stage.

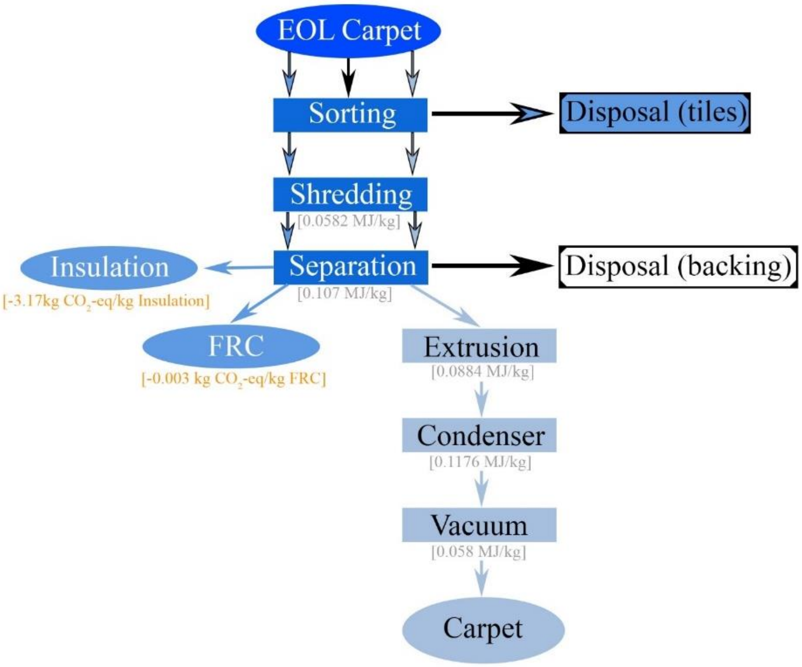


Figure 8. Sorting and disposal process of EOL carpets.

The identified downcycling methods for EOL carpet require the separation of the top layer from the backing layer. This is achieved through shredding and (air) separation. The energy requirements of this process are described by Schmidt & Cieślak (2008, p.1239). Disposal is either through landfilling or through incineration with heat and energy regeneration.

4.4 DESIGN COMMUNICATION

The created model is a complex set of computational rules, unfit to be displayed in this thesis. Instead it is opted to provide a graphical display of the system which, combined with the previous chapter, allows for easy replication of the model. This chapter briefly discusses some sub-systems, and then continues to provide the overview of the entire created model.

The following figures are based on the best-practices for system diagrams and use a “+” or “-“ symbol to signify the direction of a correlation. A positive correlation indicates that if factor A increases, factor B increases as well. For a negative correlation, an increase in A indicates the decrease of B.

4.4.1 Downcycling and recycling subsystems

The first identified subsystem is in regard to downcycling and recycling gains/costs. Figure 9 displays the identified subsystem of downcycling but is interchangeable with recycling. It describes how the quantity of material offered for downcycling affects the costs and benefits of the entire system.

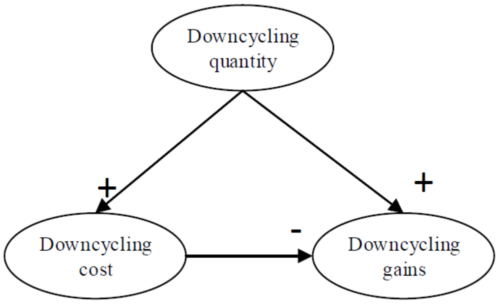


Figure 9. Subsystem of downcycling.

The more material is supplied to be downcycled, the higher the downcycling costs are. Equally, more material supplied could mean more downcycling gains (if efficient downcycling alternatives are selected). These gains are only achieved by subtracting the costs, a negative gain equals a loss. The benefits of downcycling thus depend on the quantity of supply and the costs.

4.4.2 Disposal subsystem

The disposal subsystem is a mirrored image of the downcycling/recycling subsystem as it assumes that disposal has more costs over benefits. Thus, the disposal costs are the final product, limited by the disposal gains, if any. Figure 10 displays the disposal subsystem.

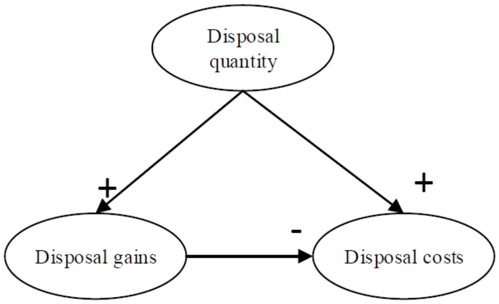


Figure 10. Subsystem of disposal.

4.4.3 Interdependency resources

For both the production resource acquirement as well as the EOL resource management stages, three different outlets have been identified. These have an interdependency, modeled by figure 11. As the full circle always describes 100% of the resources, each resource stream identifies the percentage of material that is split amongst the remaining two outlets. This figure represents the EOL resource management, an equal subsystem can be created for virgin resources, downcycled resources and recycled resources.

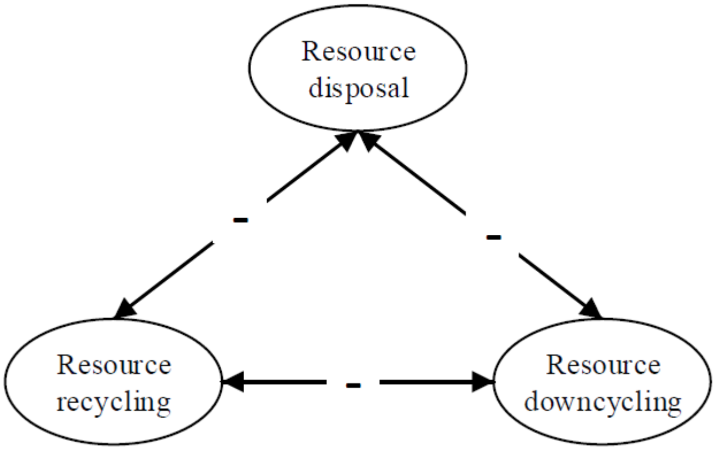


Figure 11. Interdependency of resource streams.

4.4.4 Transportation subsystems

Like the previous systems, the transportation costs are also the product of a subsystem. Here, the distance, weight of the transported product and mode specific transportation emissions and energy requirements make for the total shipping costs. The reverse logistics costs are also associated with material loss through the lifecycle, as it effectively decreases the weight of a carpet tile. The following subsystems are identified to determine the shipping costs:

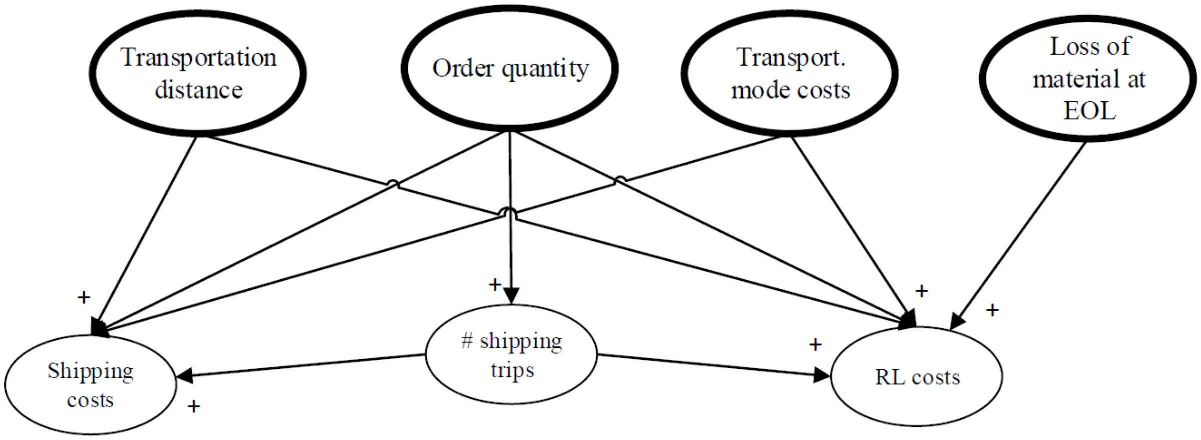


Figure 12. subsystem of transportation costs.

4.4.5 System diagram / full overview of the model

From these sub-systems, a much larger system diagram can be composed, which is presented in figure 13. This system diagram is presented as a visual representation of the entire created model. On the left are the identified means that affect the outcome of the model. In other words: these are the parameters that the industry is able to change. The effect by these parameters is modeled by the green dotted line. All means are fully discussed in chapter 4.2.4 and appendix D, as well as the effect each individual mean has on the modeling outcomes. Appendix D also discusses how realistic these measures are, what the implementation time would be, and what the costs thereof will be. All these means will be combined through morphological charts into solutions that combine a variety of means. On the top, in the oval shapes, are some of the external factors. These are factors that the industry itself cannot change directly however they do effect the calculations and the outcomes of the model. Their effect on the systems is modeled with red lines. On the right are the three main output factors or criteria. These represent the needs of the industry as identified by the introduction: fewer emissions, less waste and less reliance on virgin resources. The ovals in the middle display the calculations made by the model, the colored ovals represent the subsystems as discussed previously. An arrow represents the direction of how these factors are linked together. The "+" and "-" symbols represent how these two effects are interlinked. As discussed, there is an arrow coming from "Production quantity" going towards "shipping", indicated with a "+" symbol. This represents that whenever more carpets are produced, there will be more carpets shipped, which translate to more shipping emissions. In similar fashion, the "-" symbol represents an inversed correlation: Whenever more carpets are recycled into new carpets, the lower the virgin resource reliance will become.

To increase the legibility of the model, and allow for quicker and easier identification of interdependencies, a table is created that lists all individual factors and by which factors they are influenced. This table is presented in appendix G.

Combined with the key factors as listed in appendix F, figure 13 (system diagram), serves as the description how the model functions and what effects are modeled. A more detailed description of how the model processes all factors can be found in appendix E.

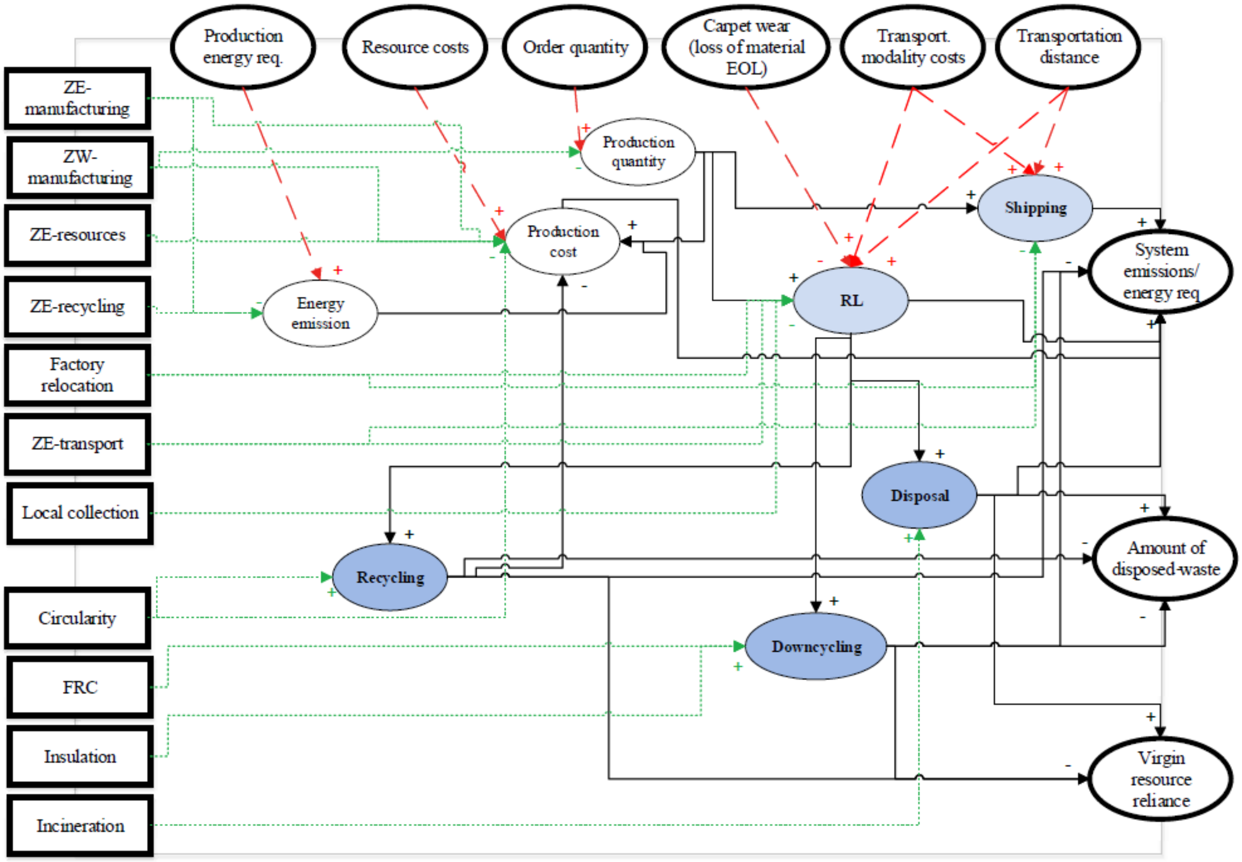


Figure 13. System diagram.

4.5 USING THE MODEL

The above created model is used to calculate the effects of the different sustainability increasing measures as described per chapter 4.2.4 on the emissions of the entire system given the input measures as detailed by appendix E. But as discussed, this model should first be able to accurately model the current situation before it can be used to calculate the effects of sustainability increasing measures. For this purpose, a nil-scenario is created. This nil-scenario is used to create the baseline through modeling the current operation, which should accurately reflect the real-life emissions of the equal system. For this nil-scenario, no sustainability increasing measures are implemented. This makes for the emissions to be calculated (through the system as discussed in figure 13) based on the following input data, determined to either be the standard (Chapter 4.3):

Carpet tile production	*Shipping & reverse logistics*	*Recycling/sorting*
Touch & Tones 103	123.2 km avg shipping distance	100% Landfill
100% virgin resources	Truck, 3-10t diesel	
Natural gas energy source	1 Trip	
1% productional waste	12% loss of material through usage	

These inputs are then processed according to the key figures as described by appendix E-F. For instance, given the distance and transportation mode, the transport emissions are calculated through the subsystem as described by figure 12. With this input and computational rules, the model returns a emission score to the user. As specified in chapter 4.2, this output entails the energy requirement, CO_2-equivalent costs and particulate matter emission of the system.

Dym et al. (2004) describe that the design should be communicated in a clear and easy to comprehend matter. In this case, the design communication entails the output figures as generated by the model. The model reports the findings in a clear and compact matter through the presentation of a table that lists the CO_2-eq. and PM_{10} emissions, as well as the energy requirements. The CO_2 emissions table expresses costs (resource acquirement; production and coloring; transportation and reverse logistics; disposal; separation of nylon from the backing; separation of backing material; emission savings through downcycling) in terms of a GWP, presented in kilograms of CO_2-equivalent costs. The energy requirement section discusses similar aspects, with the exception of the discussed GER disposed cost. This cost is merely an indication of what amount of GER is disposed, and it is not used in the calculation of the total effect. Finally, the PM_{10} table provides an overview of the emitted particulate matter. More explanation of the interpretation of these results can be found in appendix H.2.

4.6 COSTS OF THE CURRENT CARPET TILE PRODUCTION

Given the input data that reflects the current production methods, the model is designed to estimate the costs of the production of one unit of carpet tile. This is the nil-scenario, and will be the baseline score for the sustainability increasing measures. Table 7 again reflects the input data, as well as present the emission estimates as discussed in the previous section. For a full interpretation of these results, see appendix H.2.

Table 7

Model specification and results "Nil-alternative"

Production RSS		Production		Transport		Lifecycle		Reverse Logistic		Sorting	
Recycled	0%	PWR SRC	Natural gas	km	246.4	Loss of Material	12%	km	246.4	Recycled	0%
Open-loop	0%	Waste	1%	MODE	Truck, 3-10t, diesel			MODE	Truck, 3-10t, diesel	Downcycled	0%
Virgin	100%	Tot. Weight	1	# trips	1			# trips	1	Disposed	100%
										Disp. method	Landfill

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.7	TOTAL	4.9
Virgin	3.6	RL	0.1	Nylon sep.	0.0		
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

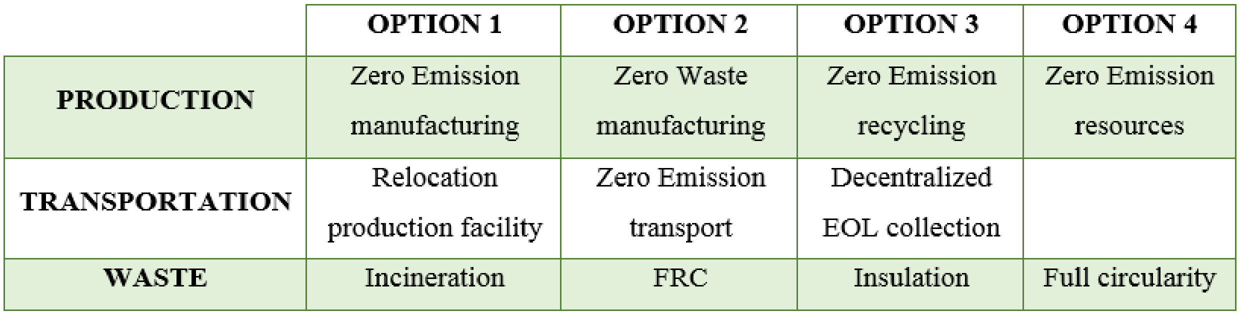
Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.0	TOTAL	78.0
Virgin	72.1	RL	1.1	Backing sep.	0.0		
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	20
Manufacturing	11	RL	4	Disposal	0		

With the modeling decisions as discussed by chapter 4, this model results a total emission of 4.9 kg CO_2-equivalents per carpet tile, a general energy requirement of 78.0 MJ and a total production of 20 milligrams of particulate matter (PM_{10}). These results are in accordance to the Environmental Product Declaration (EPD) as discussed in chapter 6.

Model development conclusion:

A model was created that is used to produce and calculate logical, explainable and realistic means to increase the sustainability of the carpet industry. This requires the model to accurately and realistically simulate the current scenario. It was further determined that the costs of the identified sustainability increasing measures should be in proportion to their costs, and their implementation time should be ten years or less. The MoSCoW methodology is used to create the model requirements. In the detailed design, the following design space was identified:



	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	Zero Emission manufacturing	Zero Waste manufacturing	Zero Emission recycling	Zero Emission resources
TRANSPORTATION	Relocation production facility	Zero Emission transport	Decentralized EOL collection	
WASTE	Incineration	FRC	Insulation	Full circularity

Through the usage of the model, it was identified that the production and shipping, as well as the usage, reverse logistics and disposal (landfilling) of one single carpet tile equals the emission of 4.9 kg CO_2-eq. units and 20 mg of particulate matter. Likewise, this production requires 79 MJ of energy.

5 CREATING SOLUTIONS

Structure:

Several means that could increase the sustainability of a carpet tile's supply chain have been identified. This chapter is aimed at presenting the identified means in greater detail and combining means to form policy measures. In section 5.1, the solution space is displayed, displaying what options are available. In section 5.2, the effects of each measure are explored and presented. Section 5.3 discusses the designed and complete solutions, which are a combination of several means.

During the literature study and through the modeling process, several means have been identified that could possibly increase the sustainability of the carpet industry. This chapter discusses the effect of these measures and combines them into a solution space. Through this solution space, a combination of measures is created to simultaneously address all three sources of resource leaks.

5.1 SOLUTION SPACE

Comprehensive and all-inclusive solutions are proposed that form a package of resource leak resolving measures, to optimize sustainability. These solutions are created through a process of morphological charts, displaying the solution space (Smith, 2007). These charts provide an overview of all possible resource leak fixes, of which one or multiple are selected to compose a range of alternatives that form one solution. The design space looks as follows, and is described in more detail in appendix I. In the morphological chart, the abbreviation of ZE represents "zero emission" whereas ZW represents "Zero Waste".

Table 8
Solution space

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

5.2 INDIVIDUAL SOLUTIONS

Before combining means into wider solutions, the individual effects are examined. Table 9 will display the individual effects of the identified means. A full overview of these effects can be found in appendix J, as table 9 only displays the percentual changes compared to the nil-alternative.

Table 9
Solution space: individual effects

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	**ZE-manufacturing** -3.5% CO_2-eq. 0% MJ -53.9% PM_{10}	**ZW-manufacturing** -1.0% CO_2-eq. -1.0% MJ -0.7% PM_{10}	**ZE-recycling*** 0% CO_2-eq. 0% MJ 0.0% PM_{10}	**ZE-resources** -74.7% CO_2-eq. 0% MJ -53.9% PM_{10}
TRANSPORTATION	**Relocation** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	**ZE-transport** -2.3% CO_2-eq. -2.3% MJ -4.6% PM_{10}	**Local collection** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	
WASTE	**Incineration** -2.2% CO_2-eq. -26.3% MJ +45.4% PM_{10}	**FRC** -5.4% CO_2-eq. -0.1% MJ +2.6% PM_{10}	**Insulation** -24.4% CO_2-eq. -6.6% MJ +2.6% PM_{10}	**Full circularity** -81.3% CO_2-eq. -81.4% MJ +14.9% PM_{10}

* not a stand-alone solution, requires downcycle or recycle flows in order to have an effect.

5.3 DESIGNING SOLUTIONS

Through morphological charts six different solution spaces are designed. These six can be found in appendix I. In this chapter, only four will be discussed, as alternatives including full circularity and zero-costs manufacturing are deemed unrealistic at this stage. Their effects are however still calculated and can be found in appendix I.2 and appendix I.5. The following four alternatives have been designed and calculated:

5.3.1 Alternative 1: Waste disposal fix

In the waste disposal fix, the main issue of landfilling is addressed by providing a solution that, amongst other things, eliminates or decreases the amount of waste that is landfilled at the end of lifecycle. It provides a better alternative for the waste product if it is deemed unrecyclable. For alternative 1, the following design space was selected:

Table 10

Design 1: morphological chart "Waste disposal fix"

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	[✓ ZW-manufacturing]	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	[✓ Local collection]	
WASTE	[✓ Incineration]	FRC	[✓ Insulation]	Full circularity

For this configuration of options, the following results were achieved:

Table 11

Design 1: modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.6	TOTAL	3.5
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-28.8%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	-1.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	71.3	Transp.	1.3	Nylon reclaim	0.2	TOTAL	56.9
Virgin	71.3	RL	0.1	Backing sep.	0.0	Change	-27.1%
Closed	0.0			GER disposed	21.2		
Open	0.0			Effect	-19.5		
Manufacturing	3.4						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	1	TOTAL	22
Manufacturing	10	RL	0	Disposal	6	Change	14%

Following these results, it can be concluded that a solution that alters the collection and processing of waste, combined with a zero-waste manufacturing method, has the power to decrease emissions and energy requirement by roughly 28% while increasing PM emissions by 14%.

5.3.2 Alternative 2: Timely fix

The second set of options is primarily focused at a swift implementation time. This alternative is designed to be in full effect within five years' time. The following options were selected that are deemed to have this quick implementation time:

Table 12

Design 2: Morphological chart "Timely fix"

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

The combinations of zero-emission manufacturing and recycling, through renewable energy sources (Solar powered in this scenario), combined with zero-emission transport (3-10t electric truck at 43% decrease in CO_2-eq.) and the recycling option that is currently available, results in the following emissions and energy requirements (table 13):

Table 13

Design 2: modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	4.3
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-11.4%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	0.4	Nylon reclaim	0.2	TOTAL	76.1
Virgin	72.1	RL	0.3	Backing sep.	0.0	Change	-2.4%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-0.2		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	4	Separating	0	TOTAL	8
Manufacturing	0	RL	4	Disposal	0	Change	-58%

Here, a relatively small change in energy requirement is observed. This is because the downcycling method of FRC is a relatively low-gains alternative. Furthermore, about two thirds of all material are still landfilled in this design, as the backing material is not recycled. Implementation of this alternative combined with waste incineration and energy regeneration would be more beneficial to the sustainability of the supply chain. But as discussed in section 3.5.2, these incineration plants are not yet able to process carpet waste and are not deemed to be compatible with EOL carpets on a short timeframe. Thus, quick implementation measures are deemed to be able to save a maximum of 11% in global warming potential, decrease energy usage by a mere 2%. The major gain in this alternative is in particulate matter emissions, a reduction of 58% is achieved.

5.3.3 Alternative 3: Recycling fix

This alternative primary focus is on finding alternatives for recycling by optimizing the value chain and production process. It uses a zero-emission energy source (wind, the most favorable energy source in terms of CO_2-equivalent emissions) for the manufacturing process and rather than collecting EOL carpet tiles at the factory, it uses the widespread network of municipal waste disposal sites for a decentralized reverse logistics operation. Here, each plant is able to separate the top layer from the backing fiber. Local companies are then to purchase these downcycled nylon fibers for insulation purposes. In a morphological chart, this alternative is based on the following design space:

Table 14

Design 3: Morphological chart "Recycling fix"

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

Giving the following modeling results (table 15):

Table 15

Design 3: modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	3.4
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-31.0%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	-1.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	71.8
Virgin	72.1	RL	0.1	Backing sep.	0.0	Change	-7.9%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-5.3		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	5
Manufacturing	0	RL	0	Disposal	0	Change	-73%

Liming the reverse logistic distance has a big effect on the emissions and energy usage of the transportation costs. Downcycling of nylon fibers for insulation purposes proves to be a very effective method for recycling, thus a steep decline of 31% in emissions is observed in this scenario. For the energy requirement a smaller change is observed. This is due to the fact that current alternatives to insulation are produced at a relatively low amount of energy, yet at high emissions. The decrease in transporting distance also has the power to reduce PM_{10} emissions by 73%. So, the change in emissions of repurposing nylon fibers is bigger than the change in energy requirement to produce one unit of insulation material.

5.3.4 Alternative 4: Budget fix

The final design space consists of low-cost focused options that compose one alternative. Here, the cost aspect is prioritized above all else. The following options were selected.

Table 16

Design 4: Morphological chart "Budget fix"

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	[✓ ZE-manufacturing]	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	[✓ Local collection]	
WASTE	Incineration	[✓ FRC]	Insulation	Full circularity

It has become apparent that the cheapest option is not always the quickest to implement. This alternative thus assumes delivery of zero-emission energy by the power company in the form of a 100% hydropower source energy contract, assumes local decentralized collection of EOL carpets and assumes these will be used in the already established downcycling method: FRC. This alternative results in the following emissions and energy requirements:

Table 17

Design 4: Modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	4.3
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-12.1%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

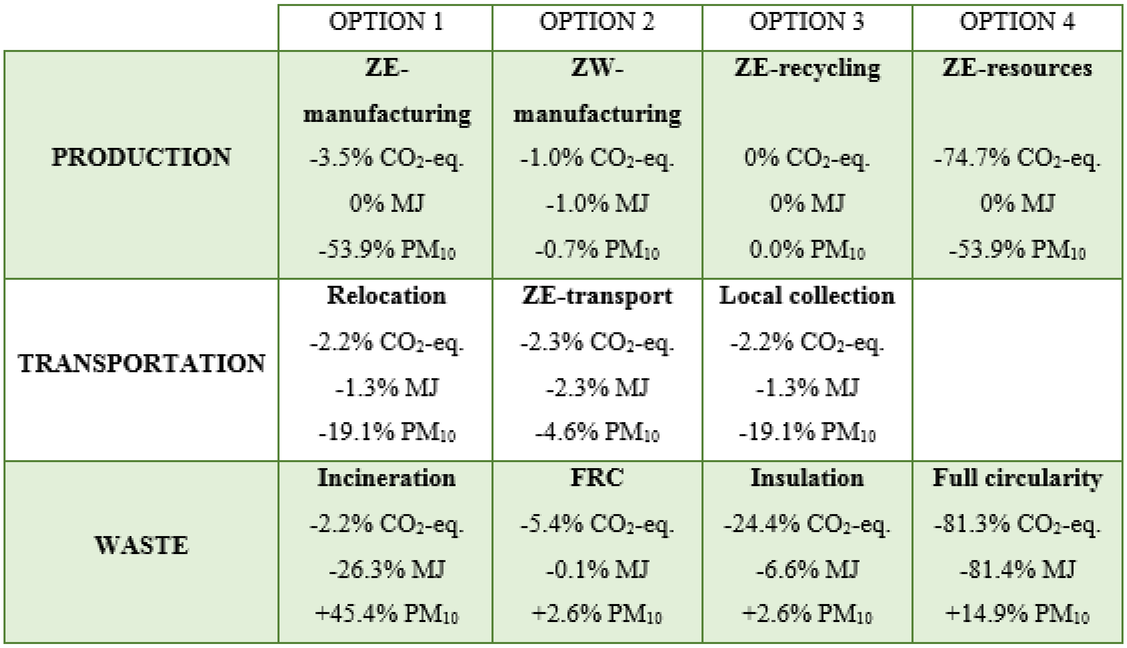
Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	76.9
Virgin	72.1	RL	0.1	Backing sep.	0.0	Change	-1.4%
Closed	0.0			GER disposed	21.3		
Open	0.0			Effect	-0.2		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	5
Manufacturing	0	RL	0	Disposal	0	Change	-73%

The budget alternative brings the least amount of gains in terms of energy saved and is closely second to least favorable alternative in terms of GWP to alternative 2: timely fix. But in terms of cost-effectiveness this scenario might pose a different story, as no heavy investments are required in electric vehicles.

Creating solutions conclusion:

The previous identified sustainability increasing measures are implemented into the model and fully quantified. The following results were obtained for the individual sustainability increasing measures:



	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	**ZE-manufacturing** -3.5% CO_2-eq. 0% MJ -53.9% PM_{10}	**ZW-manufacturing** -1.0% CO_2-eq. -1.0% MJ -0.7% PM_{10}	**ZE-recycling** 0% CO_2-eq. 0% MJ 0.0% PM_{10}	**ZE-resources** -74.7% CO_2-eq. 0% MJ -53.9% PM_{10}
TRANSPORTATION	**Relocation** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	**ZE-transport** -2.3% CO_2-eq. -2.3% MJ -4.6% PM_{10}	**Local collection** -2.2% CO_2-eq. -1.3% MJ -19.1% PM_{10}	
WASTE	**Incineration** -2.2% CO_2-eq. -26.3% MJ +45.4% PM_{10}	**FRC** -5.4% CO_2-eq. -0.1% MJ +2.6% PM_{10}	**Insulation** -24.4% CO_2-eq. -6.6% MJ +2.6% PM_{10}	**Full circularity** -81.3% CO_2-eq. -81.4% MJ +14.9% PM_{10}

Through morphological charts, these options can be bundled, as these are not naturally exclusive. This led to the creation of sustainability increasing options, or designs. The four identified fixes are categorized as follows:

Design 1: Waste disposal fix
Design 2: Timely fix
Design 3: Recycling fix
Design 4: Budget fix

The third design achieves a 31% reduction in global warming potential, a 8% reduction in (gross) energy requirement and a 73% reduction in particulate matter emissions, making it the best performing alternative on a general level.

6 VALIDATION

Structure

This chapter discusses the modeling results in terms of accuracy and probability. In section 7.1, the key data used is disputed and uncertainty is deliberately introduced into these figures. Section 7.2 discusses the extreme condition tests that were performed on the model. Section 7.3 features a more detailed analysis of the effect of uncertainty in the key figures on the results. Section 7.4 discusses the expert interviews that were held. Section 7.5 compares the modeling results to known emission figures and section 7.6 concludes if the model is suitable to be used.

The nil-alternative modeling results from chapter 4 are said to reflect the real world costs of the production of one unit of carpet tile. As this model is created based on several assumptions, limitations and demarcations, by default, the model fails to accurately display the reality. By recognizing the limitations, and through validation of the model, the results can still be used to give insights into the system. Before translating the model results into policy advice, a measure of validity is to be established. This chapter identifies how the modeling results compare to the real world case, and to what extent the results can be used/interpreted. This is known as validity testing and is achieved through several tests.

6.1 KEY DATA UNCERTAINTY

The model is created using key data from different (scientific) sources, mostly governmental approved or sanctioned sources that display Dutch averages. These key figures are e.g. the emissions of a diesel van. Key figures are in some cases hard to compute, and different researchers with different research methods might generate different emission figures. It is thus the logical consequence that emission factors, or any other key figures, are presented with a range of uncertainty, resulting in a means/median, lower limit and upper limit. Remarkably, none of the official Dutch key figures are presented in a range of uncertainty. It is thus to the researcher to determine this uncertainty.

The key figures are categorized and classified as either having a high uncertainty or a low uncertainty based on the literature. This is presented in appendix K.2. The key figures that are valued at uncertainty are assigned a 10% uncertainty increase/decrease of their initial value, whereas the highly uncertain criteria are assigned a 50% uncertainty range. The following table reflects the key data uncertainty.

Table 18
Key figure ranges of uncertainty

Model key figure	Uncertainty	interval
Resource specific key figures	High	[-50%,50%]
Energy specific key figures	High	[-50%,50%]
Downcycling means	Low	[-10%,10%]
Disposal: Landfill	High	[-50%,50%]
Disposal: Incineration	Low	[-10%,10%]
Production energy requirement	Low	[-10%,10%]
Vehicular emissions	Low	[-10%,10%]

6.2 EXTREME CONDITION TEST

The first validity test is an extreme conditions test. The model is subjected to unrealistically high and low values to observe how the model processes this input. If the model behaves unexpectedly, it could indicate a flaw in the design. For this validity test, several hypotheses are formulated that indicate how the model is anticipated to behave. The following hypotheses were confirmed:

- An increase in the required amount of material will increase resource costs in the same percentage, but not the total system costs (appendix K.3.1)
- If the shipping distance of open-loop obtained recyclable nylon 6 is extremely high, the downcycling costs will be higher than virgin resource costs (appendix K.3.2)
- If the shipping costs is extremely high, the total cost of the system will approach the pure effect of shipping (appendix K.3.3)
- If the lifespan losses of material to a carpet tile are 100%, there should be no RL movement (appendix K.3.4)
- If the quantity of downcycled material is extremely increased, the downcycling gains are equally increased as well (appendix K.3.5)

The model was deemed to behave well under extreme conditions but failed on one facet (appendix K.3.6). Shipping emissions do not have a lower-limit, as the unit tonkilometer does not facilitate in minimum emissions. Meaning that an almost empty cargo vehicle across the world would result in near zero emissions according to the model. This is covered by the model by indicating a minimum loading capacity for cargo vehicles.

The user is able to deliberately break the model by modeling more material being recycled than is available for recycling. The model balances any recycling/downcycling efforts beyond 100% by assuming a negative disposal quantity, creating even bigger false readings. The model does warn the user when an input is detected indicating recycling/downcycling efforts beyond 100% material availability. It is thus more of a user-input error rather than a failure of the model. Given the purposes of the model, this is not deemed a limiting factor to the validity of the model.

6.3 SENSITIVITY TEST

During the sensitivity test, (appendix K.4), the model parameters are changed into two different scenarios to reflect the findings of uncertainty in the key figures. These two scenarios reflect the “best case scenario” and “worst case scenario”. The general effect of this uncertainty adaptation was a 46% increase/decrease in GWP, a 47% increase/decrease in energy requirement and a 28% increase/decrease in PM_{10} emissions. The sensitivity test did not result in different best-in-class alternatives, but did alter, as expected, the general modelling results. The uncertainty of the modeling outcomes will be considered in the interpretation of the results, but the sensitivity test proved that the behavior of the model did not change unexpectedly.

6.4 EXPERT REVIEW

This model is validated through external sources with high expertise in the field of carpet recycling and reverse logistics. For this research, Dr. Steve LeMay and Dr. Marilyn Helms were found willing to access the model, modeling results and created scoring scenarios. Unfortunately, by the time of writing, no formal validation was yet received from either of these world leading scientists. Some general feedback was received, but both Dr. LeMay and Dr. Helms have not yet replied to the final exchange of modeling results. This section is included in the validity chapter as a placeholder for their feedback in case of a revision and as a reminder of the importance of expert validity testing.

The model was however validated by the industry with the aid of Interface EMEA. During an arranged validation- and feedback session, the model and the validation criteria received excellent reviews. Without any ambiguity, E. Oudenbroek (VP operations, Interface, representing the industry) agreed with the findings and expressed her contentment with how the model was able to incorporate the needs and requirements of the industry.

6.5 EPD VALIDATION AND LIKELIHOOD

Interface's Touch & Tones 103 carpet tile's environmental impact is assessed by independent scientists. Through this public Environmental Product Declaration (EPD), the total emissions of the cradle-to-grave cycle of the particular carpet is known. With the absence of academic validity testing, this proved to be a major source of validation.

Raw material supply, transportation, manufacturing, delivering to customer, and EOL collection of carpets combined cause a GWP of 4.152 kg CO_2-equivalents according to the manufacturers EPD, based on the parameters as described in chapter 4.5. Based on virgin resource GWP costs as estimated by CE Delft & Rijksdienst voor Ondernemend Nederland (2018), combined with the manufacturing costs as identified by Li (2007) and the shipping/RL costs as discussed in section 4.3.3, the model returns a GWP of 4.143 kg CO_2-eq., a 0.2% deviation from the EPD based on unrelated data sources. The EPD argues that landfilling does not cause any direct CO_2-eq. emissions, which is disputed by this research through the findings of (Arena et al., 2003; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017). In all, excluding the waste processing options, the model produces a GWP that is in an acceptable range from the findings of the EPD, with a slim distribution of error across all factors.

Besides emissions, the energy requirement is also validated. Researchers estimated the production costs of a nylon carpet to be at 25.42 MJ per 0.09 m^2 nylon carpet tile, which translates to 70.61 MJ per 0.25 m^2 carpet tile (Haines et al., 2020). The model results an energy requirement for the production stage of 72.06 MJ based on unrelated data points. This equals a deviation (over estimation) of 2.1%, equally satisfying the range of acceptable output figures.

6.6 USABILITY OF THE MODEL

There are several limitations to the model, which prevent it from truly modeling every aspect of a carpet's supply chain. Vehicular transportation is for instance a product of e.g. weight, but the model does not facilitate in a lower limit. However, based on the EPD validation, the opinion of the industry and given the limitations of the model, it is deemed fit to be used for this study. The emission output is likely, the factors are well established, and most importantly, the identified measures all have a scientific backing. And as the model is used to calculate the effects of certain measures compared to the nil-alternative, modeling mistakes are equal to both scenarios, limiting its effect on the result. In all, it was concluded that the model can be used as a rough exploration and indication of effectiveness of different sustainability increasing measures.

Validation conclusion:

An attempt is made to validate the model with (academic) experts in the field of carpet tile logistics. Unfortunately, this validation was not achieved through both the academic experts, as well as the branch organization of carpet manufacturers. The model was however validated through an uncertainty analysis, extreme test, sensitivity test and by one representative of the industry. The model was validated through the manufacturer’s environmental product declaration, an independently created assessment of the environmental costs of a carpet tile. The created model in this study produces an estimated environmental impact that is just 0.2% higher than the manufacturers EPD indicates. Through this comparison, the model is assumed to produce likely and usable results.

7 POLICY EXPLORATION

Structure

In this chapter, a policy advice is issued regarding the adaptation of sustainability increasing measures. The first section, 7.1, discusses how the different alternatives can be rated in a multi-criteria analysis. Section 7.2 gives an overview of the identified scenarios and the score cards. Section 7.3 explains the need for governmental intervention through the use of analogies. This chapter closes by issuing a policy advice in regard to adaptation of the alternatives in section 7.4.

With the establishment of different alternatives comes the question which is the best performing measure. This chapter aims to identify which of the created, all-encompassing, solutions is most effective in achieving a reduction of landfilling and emissions, while keeping the needs and requires of the industry in mind. This is achieved through the adaptation of score factors. Score factors indicate key elements to the industry that describe the likelihood of adaptation, ranging from continuity to increased circularity. Through these score factors, a framework can be established in the form of a scorecard, which evaluates each solution based on multiple score factors. Following this evaluation, a policy advice is issued on how sustainability can be achieved. Chapter eight will feature the policy advice from this chapter, combined with all previously obtained results, to form a general conclusion on the likelihood of adaptation, implementation and effectiveness.

7.1 INDICATORS FOR A SUITABLE SOLUTION

Until now, this study falsely assumed a willingness by the industry to implement any sustainability increasing measure that is presented. Carpet manufacturers have shareholders to please and other standards to comply to. It is thus a false assumption that any recommendation here will be indiscriminately adapted into the day-to-day operations by these manufactures. Carpet manufacturers have a set of previously undiscussed factors they deem of importance. These criteria are to be met or mitigated elsewhere in order for an alternative to become an actual implementable measure. These factors are expressed as “score factors” and are validated by the industry themselves.

7.1.1 Score factors

The following factors discuss the acceptance of any sustainability increasing alternative. These factors originate either from the literature as discussed in the formulation of the MoSCoW list or have their origin in the annual reports of either Tarkett/Desso or Interface. They are categorized in subcategories.

The suggested alternative should:

Table 19

Scoring criteria sustainability increasing solutions

Factor	Main objective
Resilience	
Decrease the reliance on one supplier	The alternative should spread the resource flow across several supplier streams to ensure continuity and minimize risk.
Minimize risks for manufacturer	The gains of the alternative should be somewhat certain in order to justify the adaptation. High risks for minimal gains are deemed unacceptable and could pose issues for the financial health of the manufacturer.
Ensure continuity of supply	The production facility should be kept in operation during the transition in order not to cause any delay in the fulfilment of orders.
Decrease virgin and exhaustible resource reliance	The usage of virgin and/or exhaustible resource sources should be kept to a minimum in order to prevent eventually running out of resources to manufacture carpets.
Financial	
Facilitate growth	In any case, the alternative should facilitate growth in financial terms. This means that the alternative does not necessarily have to be profitable from the start, but it should enable bigger financial gains to be had.
Yield a positive Return of Investment	The return of investment for implementation of the measure should be positive. This might indicate a direct savings in terms of monetary assets, or cause for instance increased sales and as such further strengthen the financial position of the manufacturer.
Limit costs for customer	The implemented measures should not lead to an increased unit cost for the customer.
Logistical	
Divert EOL from landfills	The measure should see to the fact that the quantity of product landfilled decreases.
Minimize transportation distances	The transportation distance, and the costs associated with transportation, should be kept to a minimum through spreading outlets or by any other means.
Collect EOL product	The manufacturers claim that ownership of EOL product is a key factor in achieving sustainability. Thus, the means should facilitate the manufacturer reclaiming the EOL product.
Image	
Promote green image of company	The measure should have a positive effect on the image of the company, as image could affect sales.
Ensure quality	The quality of a carpet is a key selling point and thus should not be decreased through implementation of the means.
Decrease environmental effects	The means are to decrease the environmental effects, which are modeled through emissions and energy reliance.

Some factors, like specifics for emissions, are not included in the above stated table. This is due to the fact that these factors are the primary reason for the establishment of this design paper. As such, they are already heavily featured in the paper and present the core functionality of the modeling tool on which these means will be tested. Although the results are insightful, the functionality of "should decrease emissions" is a design criterion rather than a scoring criterion, as alternatives that increase emissions should not be implemented into the model in the first place.

7.1.2 Key Performance Indicators

Regardless of the missing design parameters, the factors of table 19 are rather vague and are less focused on the data obtained from the model. Management generally prefers more concrete numbers regarding costs, gain and other factors deemed of importance, which are already generated through the model. This is why Key Performance Indicators, also known as KPIs, are included in the scorecard setting. These KPIs are a measure of the effect of the suggested alternative in quantified units. The model itself results in KPIs, which are presented in the previously featured GWP, energy and particulate matter tables. As there is high uncertainty in the described scenarios, these KPIs are part of, but not deemed key to, the formulation of a final policy advice: minor changes in the future could greatly affect the outcomes of these KPIs. This chapter briefly touches upon the uncertainty and the effect of uncertainty on these KPIs; however, this analysis is anything but all-inclusive and should be treated as such.

7.1.3 Designing scoring framework

In order to make the different identified alternatives comparable in an easy to review and comprehensible manner, a scorecard framework was created based on the scorecard theory as described by De Haan & De Heer (2012). Within this scorecard all identified alternatives are listed in a single table and are scored on every individual factor as discussed in chapter 7.1 and 7.2 depending on the scenario. It is important to note that the alternatives are scored compared to each other. Thus, the best performing alternative will show better ratings, but it does not indicate that this alternative is the optimum scenario. This rating is only based on the means included in the study and does not accurately display the entire pool of possible means over time.

A unit had to be devised to measure the performance of each alternative. Factors like image of a company are hard to measure. For the identified factors from chapter 7.1, a rating scheme is developed that is based on a five point Likert scale, making the rating of ordinal scale. This means that the alternatives have no absolute zero and the distance between the categories is not necessarily equal. The Likert scale is presented in double negative to double positive, meaning {- -, -, 0, +, + +}, in which the double positive is the best, the double negative is the worst performing alternative. These effects will be coded ranging from -2 (double negative) to +2 (double positive) in order to compare the overall scoring. The individual scores will also be color coded for legibility. Besides the Likert scale, some factors are identified as hit-or-miss factors, meaning the alternatives either fulfills this factor or does not adhere to this factor. This is indicated with a checkmark for fulfilment (✓), uncertainty (?) or a cross mark for failing to comply (✕). The KPIs are presented in the factual data that is obtained through the model. The following table (Table 20) gives an overview of the created factors and units that are used in the framework.

Table 20

Scoring units and abbreviations in framework

Factor	Abbreviated as	Unit
Resilience		
Decrease the reliance on one supplier	Sup. Rel.	{- -, -, 0, +, + +}
Minimize risks for manufacturer	Risk	{- -, -, 0, +, + +}
Ensure continuity of supply	Sup. Cont.	{- -, -, 0, +, + +}
Decrease virgin and exhaustible resource reliance	Virgin RES	{- -, -, 0, +, + +}
Financial		
Facilitate growth	Growth	{- -, -, 0, +, + +}
Yield a positive Return of Investment	RoI	{- -, -, 0, +, + +}
Limit costs for customer	Purchase	{- -, -, 0, +, + +}
Logistical		
Divert EOL from landfills	Landfill	{- -, -, 0, +, + +}
Minimize transportation distances	tkm	{- -, -, 0, +, + +}
Collect EOL product	RL	✓, ✕
Image		
Promote green image of company	Green img.	{- -, -, 0, +, + +}
Ensure quality	Quality	✓, ?, ✕
KPIs		
Implementation costs - estimate	€	{- -, -, 0, +, + +}
Implementation time – estimate	Time	{- -, -, 0, +, + +}
GWP per carpet tile (model results)	GWP/unit	[CO_2-eq./unit]
Energy requirement per carpet tile (model results)	Energy/unit	[MJ/unit]
Particulate matter per carpet tile (model result)	PM_{10}/unit	[grams/unit]
GWP savings per carpet tile (model results)	GWP%	[% savings/unit]
Energy requirement savings per carpet tile (model result)	Energy%	[% savings/unit]
Particulate matter savings per carpet tile (model result)	PM_{10}%	[% savings/unit]

7.2 SCORING ALTERNATIVES

Using the scoring framework as discussed in the previous section, the alternatives are compared to each other and to the nil-alternative in a rating experiment. This experiment compares all available alternatives in terms of performance, marking them in order of best-performing (+ +) to worst-performing (- -). These symbols translate to a numerical score of -2 (worst) to +2 (best), allowing all categories to be summed in order to receive a total performance measure. As this total score could lose some information, another evaluation method is presented in the total counts of each score. The color coding corresponds with the scoring, marking the best scoring alternative dark green, the second best light green and the middle alternative yellow. Similarly, the worst performing alternative is dark red, whereas the second to least preferable is colored orange.

7.2.1 Scenario 1: no governmental intervention

In the first scenario, all alternatives are evaluated based on a scenario on which there is no governmental intervention. This means that any alteration of the nil-alternative will be the responsibility of the carpet industry and as such will carry the costs and liabilities. The following scores are created, explained in appendix I.

Table 21

Scorecard scenario 1: no governmental intervention

	Nil-alternative	Alternative 1: Alternative waste disposal	Alternative 2: Timely adaptation	Alternative 3: Recycling innovation	Alternative 4: Budget friendly
Resilience					
Sup. Rel.					
Risk	+ +	- -	0	-	+
Sup. Cont.					
Virgin RES	- -	+ +	-	+	0
Financial					
Growth	0	+ +	- -	+	-
RoI	+	- -	0	-	+ +
Purchase	+ +	- -	-	0	+
Logistical					
Landfill pot.	0	+ +	- -	+	-
tkm	-	+ +	- -	+	0
RL					
Image					
Green img.	- -	+	0	+ +	-
Quality	✓	?	✓	✓	✓
KPIs					
€	+ +	- -	-	0	+
Time	+ +	- -	-	0	+
GWP/unit **GWP%**	4.9 kg 0%	3.5 kg -28.8 %	4.3 kg -11.4 %	3.4 kg -31.0 %	4.3 kg -12.1 %
Energy/unit **Energy%**	78.7 MJ 0%	57.3 MJ -27.2%	76.3 MJ -3.0 %	72.2 MJ -8.2 %	77.3 MJ -1.8 %
PM_{10}/unit **PM_{10}%**	20 mg 0%	22 mg 14%	8 mg -58%	5 mg -73 %	5 mg -73 %
SCORE	1	0	-9	11	6
+ +	5	5	1	4	3
+	1	2	0	5	4
0	2	1	5	3	3
-	2	0	5	2	4
- -	4	6	3	0	0

7.2.2 Scenario 2: Compensated startup costs for sustainability

The second scenario, based on the advise of Baedts (2012, may), assumes a cost-free implementation of sustainability increasing measures by the industry. This means that for instance incineration plants capable of dealing with carpets will be built by the government. This results in the following scorecard:

Table 22

Scorecard scenario 2: costs compensation

	Nil-alternative	**Alternative 1: Alternative waste disposal**	**Alternative 2: Timely adaptation**	**Alternative 3: Recycling innovation**	**Alternative 4: Budget friendly**
			Resilience		
Sup. Rel.					
Risk	+ +	- -	0	-	+
Sup. Cont.					
Virgin RES	- -	+ +	-	+	0
			Financial		
Growth	-	+ +	- -	+	0
RoI	- -	+ +	0	+	-
Purchase	- -	+ +	0	+	-
			Logistical		
Landfill pot.	0	+ +	- -	+	-
tkm	-	+ +	- -	+	0
RL					
			Image		
Green img.	- -	+	0	+ +	-
Quality	✓	?	✓	✓	✓
			KPIs		
€	+ +	- -	-	0	+
Time	+ +	- -	-	0	+
GWP/unit **GWP%**	4.9 kg 0%	3.5 kg -28.8 %	4.3 kg -11.4 %	3.4 kg -31.0 %	4.3 kg -12.1 %
Energy/unit **Energy%**	78.7 MJ 0%	57.3 MJ -27.2%	76.3 MJ -3.0 %	72.2 MJ -8.2 %	77.3 MJ -1.8 %
PM_{10}/unit **PM_{10}%**	20 mg 0%	22 mg 14%	8 mg -58%	5 mg -73 %	5 mg -73 %
SCORE	-7	8	-8	14	2
+ +	4	7	1	4	2
+	0	2	0	7	3
0	1	1	6	2	4
-	3	0	4	1	5
- -	6	4	3	0	0

7.2.3 Best performing alternative

There are two methods of looking at the above created scorecards. The first method looks at the score summation, indicating the average performance of each alternative. This is in accordance with the Utilitarian approach, in which it is assumed that the best alternative is chosen. Recent shifts in literature however hint towards a second evaluation option, which assumes that humans behave less rational. Chorus (2010) argues that decisions are primarily driven by (random) regret minimization, thus assigning heavier weights on the least-favorite alternatives. The following results were obtained:

Table 23

Alternatives ratings

Scenario 1	**Best-in-class**	**Second best**	**Middle**	**Second to least**	**Least**
Utilitarian	**Alternative 3** Recycling alt.	**Alternative 4** Budget alt.	**Nil-alternative**	**Alternative 1** Disposal alt.	**Alternative 2** Timely alt.
Regret aversion	**Alternative 3** Recycling alt.	**Alternative 4** Budget alt.	**Nil-alternative**	**Alternative 1** Disposal alt.	**Alternative 2** Timely alt.
Scenario 2	**Best-in-class**	**Second best**	**Middle**	**Second to least**	**Least**
Utilitarian	**Alternative 3** Recycling alt.	**Alternative 1** Disposal alt.	**Alternative 4** Budget alt.	**Nil-alternative**	**Alternative 2** Timely alt.
Regret aversion	**Alternative 3** Recycling alt.	**Alternative 1** Disposal alt.	**Alternative 4** Budget alt.	**Nil-alternative**	**Alternative 2** Timely alt.

In both scenarios and evaluation methods, Alternative 3 is the best-scoring alternative out of the five created alternatives. Alternative 3 features the highest gains through the downcycling of nylon fibers for insulation purposes and landfilling the remaining material. It achieves high environmental scores and is middle of the pack in terms financial burdens and resilience. The least favorable alternative in all four scenarios is alternative 2. The high investment costs, long return of investment period and range limitations of zero-emission transportation means make it score below average on this rating chart. Alternative 4, the cheap-implementation plan, also scores high depending on the governmental policy. The policy advise will reflect upon these results further.

7.3 GOVERNMENTAL INTERVENTION

As discussed previously, the government has an invested interest in EOL solutions for carpet tiles. This is due to a complicated assignment of problem ownership. Whenever a carpet tile is produced, manufacturing emissions are accredited to the manufacturer. But then the carpet tile is sold to a consumer: a transaction follows in which the full ownership of this carpet tile moves from the manufacturer to this Dutch citizen. At the end of the lifecycle, this consumer disposes of the carpet through the best available means: the “milieustraat”. Here, the ownership of this carpet tile transitions from the carpet owner to the government/city council. In corporate settings, carpet removal will be part of the contract price and disposal will occur at a fee for the user. In both cases the carpet manufacturer suffers no negative consequences of the disposal of the product. As EOL carpets are non-recyclable, the current collection processes of EOL carpets by the manufacturers are out of free will to either enhance the public image or to provide a service to the customer. There is no incentive to reclaim carpets as observed in the score cards (all alternatives fail on the RL criteria). Through the means of analogies, it is investigated if governmental intervention could change this.

7.3.1 Analogy finding

There are examples of industries that have successfully closed the loop. Examples of this are the paper, glass and PET-bottle recycling industries. These materials are all collected at the EOL stage and are (successfully) transformed into new, equally valuable, products. This section will look into these sectors and the ways how they achieved circularity in sight of the findings on the carpet tile's EOL difficulties. As PET-bottles provide a monetary incentive to be recycled, paper and glass do not, they will be discussed in two individual categories.

7.3.2 Glass & Paper circularity

Glass and paper are 100% recyclable and thus have the ability to contribute to a zero-waste economy. The central government implemented laws that oblige cities to separately collect glass and paper, facilitating the recycling of these materials (Wet Milieubeheer Hst.10 afvalstoffen). A market was established for these high value EOL resources, with high demand. Supply however did not occur naturally without stimuli other than doing good for the planet.

Household waste collection and processing is a paid service. This might be through fixed costs per unit or through general taxes based on averages, but the user is taxed per unit of household waste. Facilitating the collection of glass and paper separately from this household waste allows the user to decrease the weight (and costs) of household waste. This way, a financial motive is provided to a household to recycle these materials. By providing easily accessible collection points, these thresholds were further reduced for the consumer. Industrial quantities of EOL paper or glass are often sold, providing a financial motive for waste separation. Besides environmental awareness, the government nudged the citizen towards waste separation by providing financial stimuli, thus creating supply. The market matched this supply with demand and a closed-loop circularity flow was formed for glass and paper.

7.3.3 PET-bottle circularity

For large PET-bottles the government implemented another tactic to ensure a supply of EOL product. The bulky nature of large bottles makes it a bigger inconvenience to separate as it requires more space. In order to prevent these bottles being crushed and mixed in with the household waste, a deposit system was introduced. The consumer pays a small fee when purchasing the bottle, which will be paid back upon returning the bottle. This psychological effect turned out to significantly decrease the amount of PET-bottle waste, as the Dutch government expands this policy to include smaller bottles and aluminum cans as well (Koopmans, 2017). Again, the demand for recycled PET occurred naturally, as recycled PET requires less than half the energy of virgin PET to be molded (Benavides, Dunn, Han, Biddy & Markham, 2018). PET-bottle recycling is currently the responsibility of bottle-outlets, be it supermarkets or gas stations. A deposit is made when purchasing a bottle. This deposit is managed by an independent foundation and is returned to the client upon return. The collection point of plastic bottles is able to sell this EOL material back to the supplier or processing facility and thus a market is established.

7.3.4 EOL carpet tile collection strategy

Comparing both analogies to the carpet market, it can be concluded that there are opportunities to establish a supply flow of EOL carpets. Consumers and companies have shown to be incentivized by financial motives to recycle, and EOL carpets have a proven worth. But here the similarities between carpet and paper/glass/PET-bottles stop. An important distinction is made between small household quantities of EOL product and larger, industrial, EOL quantities. The strategy of EOL carpet collection will be discussed for both these sources of EOL product.

7.3.4.1 Consumer quantities of carpet

In a similar fashion to paper and glass, consumers are taxed for throwing carpet in the household waste through the weight of their household waste. The availability of a (free) deposal method, being the recycling center, offers a seemingly financial stimulus to offer EOL carpet tiles for recycling. This method is effective up to a certain point. A consumer is only allowed to visit the recycling center a limited amount of times free of charge, and only with a certain quantity of carpet. Through municipal taxes these visits to the recycling center are factually already paid for. Visiting the recycling center regularly or with larger amounts of carpet will result in a larger disposal fee.

This proves to be problematic in terms of responsibilities and problem ownership. During the lifecycle, a carpet becomes the burden of the consumer and at the EOL, the city/municipality is supposed to take care of it. According to the findings of de Kok & van den Acker (2019, march), the city/municipality fails on the recycling policy. In the “milieustraat”, carpets are not separated from higher value fabrics like clothing, thus requiring extra effort of separation. These carpets are then deemed unfit for recycling and are sent back for landfilling. This indicates that the city/municipality has failed to establish a market for EOL carpets.

Making this establishment of a market the responsibility of the carpet manufacturer, rather than of the city/municipality, has several advantages. It offers a more justified distribution of costs and gains and incentivizes the carpet manufacturer to produce carpets that are more easily recyclable. With the establishment of a market, EOL carpets gain value. These gains can be used to compensate the losses that occur when processing the non-recyclable components of the EOL carpets by the city/municipality. In the scenario as described, carpets remain the financial responsibility of the manufacturer either through a fund (per weight) or through identification of the manufacturer. The recycling plant is then the beneficiary of any financial gains by reusing some of the EOL material.

This construction is to fix the demand for EOL product, but it does not alter the supply. In the now-created scenario, the financial burden of EOL carpets is assigned to both the carpet manufacturer as well as the consumer, as this consumer still has to pay to dispose of the carpets at the recycling center. With the new construction, the consumer is to be liberated of any financial burden of the processing of these carpets. However, by doing so, any incentive to correctly recycle carpets might also be lost. The PET-bottle analogy might provide a solution for this scenario. Both PET-bottles and carpets are bulky, awkwardly handing products which thus require more effort to recycle. A deposit construction could ensure a recycling effort by the user. At the purchase phase of a new carpet tile (which poses an easy unit) the consumer has to pay a small amount extra in deposit, which is returned to the consumer when handing in the carpets again at the end of its lifecycle.

There are a few issues regarding a deposit construction on carpets that might reduce the acceptance of this construction by the public. Contrary to PET-bottles, carpets have a lifespan of 10-15 years. Thus, buying any carpet effectively increases the price as the invested money depreciates 3% each year for the consumer (based on the most current discount figure). It basically offers the consumer a 10 year investment plan without interest. Besides the willingness to pay by the public, it does not offer a solution for the current carpets for which no deposit was paid. This policy would thus require an implementation period of 10-15 years to come into full effect.

7.3.4.2 Industrial quantities of carpet

The previous description is aimed at small amounts of carpets owned by citizens. There is however a second source of supply, being institutions and the construction industry. Called industrial quantities, these sources are e.g. a big company building renewing all its carpets. The renewal of carpets on this scale often occurs through a contractor. This contractor either offers paid disposal services or can arrange a recycling effort by the supplier of the new carpets. When EOL carpets gain value through an established market, this contractor suddenly has a valuable product that he/she can sell to the highest bidder. This ensures recycling efforts but provides little incentive for the carpet manufacturer to establish this market.

This effect could be compensated by a universal tax on carpets, with the proceeds of this tax going back to the carpet manufacturer. However, this would mean that the customer still ends up paying for the EOL product. A deposit system on a larger industrial scale is also less likely to be adapted due to the high costs and possible changing ownership of the office space. A third option is to is to make contractual obligations between a carpet manufacturer and the customer, ensuring that the carpet manufacturer is also responsible for the collection of said carpets. It creates a lease construction, in which the carpets remain the property of the carpet manufacturer. Through a penalty cause, either party failing to oblige on the EOL collection can be penalized to the extent that the advantage of owning valuable EOL product is lost. This ensures that the carpet manufacturer also reclaims carpets. This contract can be included in the rental agreement for corporate offices etc. Although this scenario provides clear regulations and distinct ownership, a risk lies in the possibility of a carpet manufacturer going bankrupt. In this case, the customer gains ownership of the carpet tiles and is able to reap the reward of the EOL product thus still guaranteeing recycling efforts.

7.3.5 Shifting responsibilities

The biggest flaw in the supply chain of carpets is in regard to the ownership of the product. An EOL carpet tile is notoriously hard to recycle. After being sold to the client/customer, this carpet is no longer the responsibility of the manufacturer. This means that the manufacturer has little incentive to produce carpets that are more easily recyclable. Regulations can be formed that assign the ownership of the EOL product to the manufacturer of carpets. For consumers, this entails a deposit system and for large industrial quantities, a leasing contractual obligation would ensure the correct ownership of EOL product.

7.4 POLICY ADVICE

There are several flaws discovered in the cradle to grave process of a carpet tile. The industry producing the carpet is not responsible for the disposal of the EOL product, thus incentive is lost to produce an easily recyclable carpet. The first order of business is to make the carpet manufacturer (or industry) at least financially owner of the EOL product. Thus, the government is to get involved. Through disposal taxes, each produced carpet can be taxed to compensate the costs of disposal. Facilitating for recycling, this tax is to also offer an incentive for carpet manufacturers that reclaim carpets for recycling. With the carpet manufacturer now stimulated to reclaim carpet, a further incentive is to be added: the establishment of a market. EOL carpets currently have no use and as such hold little logistic value. There are however industries identified that could benefit from EOL carpet tiles. This indicates market failures, possibly due to the high investment costs of carpet tile processing machinery. The policy advice by de Baedts (2012, may) is even more encouraged by this study: the government could facilitate the establishment of a market of EOL carpet tiles by decreasing the investment costs for recycling machinery. The financial means for this facilitation can be obtained (partially) through the carpet tax, as well as a partial decrease in disposal costs. With the establishment of clear ownership of the EOL product and a market for this product, the final step remains ensuring a steady supply stream. For the general public, non-commercial carpet owners, a deposit system just like the Dutch PET-bottle “statiegeld” is advised. Here the customer pays a small amount of deposit on every carpet tile, which goes into a foundation. Upon collection of these carpets, the customer regains the deposit. For corporate and industrial clients, a contractual leasing-construction is advised, in which the carpet manufacturer remains the owner of the carpet tiles.

The biggest gains appear to be in the recycling of carpet tiles to form insulation for buildings. The literature suggests that nylon could be used for insulating purposes, but that this was deemed too costly. Financial compensation by the government could offset this cost-gain balance and facilitate the establishment of a new market for EOL carpet fibers. FRC is another alternative for EOL carpet fibers, however in terms of sustainability the creation of FRC is ill-advised. Contrary to regular concrete, FRC cannot be recycled. And with a maximum of 2% nylon content, FRC poses a much bigger landfill potential.

The separation of nylon fibers from the backing material is a relatively easy and cheap process. In a fully airtight shredding/separation system this can even be achieved without any emissions. As these machines are not extremely sophisticated, a bigger gain in sustainability can be achieved by limiting the reverse logistic distance. A well-established reverse logistic system as hinted on by Cline et al (2015) resulted in a scenario in which EOL carpet tiles are recycled decentralized. Meaning every municipal recycling center has the ability to process EOL carpet tiles by separating the nylon fibers from the backing material. The nylon fibers can then be sold to local insulation companies, and the remaining backing material is then locally disposed. This reduces transportation emissions drastically. Furthermore, all carpet manufacturers are encouraged to switch to fully renewable energy sources.

Policy exploration conclusion:

An increase in sustainability can only be achieved once these measures are implemented. This willingness of implementation is primarily through the carpet manufacturers, but the government could also be a large driving force behind adaptation of sustainability increasing measures. Thus, a two-scenario multi-criteria analysis was conducted, in which the likelihood of adaptation of these sustainability increasing measures was explored. Although there was a clearly preferred alternative in all scenarios, a major obstacle for implementation proved to be the lacking of a demand for the EOL product. Without the establishment of this market, no downcycling gains can be achieved and the implementation will be in vein. The carpet industry can be partially held responsible for the creation of this problem, as they are not incentivized to create easily recyclable carpets. It was thus identified that the establishment of a product-service system for the carpet industry could be an effective tool to increase the industry’s sustainability.

8 CONCLUSION

Structure

This chapter provides on overview of the full thesis. Section 8.1 discusses the results to each individual sub-question. In section 8.2 the main research question is answered, which is the logical result of the previous conclusions. Section 8.3 advices on future research and section 8.4 gives a reflection on the study.

This final chapter marks the end of this thesis. Here, the previously obtained results are condensed, processed, and a general conclusion is formed. This is achieved through first discussing the findings to each individual sub-research questions. These lead to a general conclusion, which is also the main research question. Following the answering of this central research question, a reflection is presented on this work. Finally, a suggestion for future research is presented.

8.1 CONCLUSIONS TO THE SUB-QUESTIONS

The objective of this research was to design a sustainable supply chain for the Dutch carpet tile industry by the year 2030. This research set out to approach this design through the answering of several sub-questions. These sub-questions will be answered in this chapter.

What is the logistical path of one unit of carpet tile, from production to EOL (cradle-to-grave)?

A carpet tile is either produced out of virgin resources, downcycled resources, recycled resources, or a combination of these factors. After the production process, these carpet tiles are shipped to the customer where they are used. At their end-of-lifecycle, the carpets are returned to either a recycling station or directly to the manufacturer. A sorting happens: some carpets are destined for disposal (either landfilling or incineration), some carpets are downcycled to make fiber reinforced concrete, and some are returned to the manufacturer in hopes of repurposing. A lot of flaws were discovered in this system. Recycling efforts of carpets was deemed non-existent, even though manufacturers are actively stockpiling carpets in hopes of achieving circularity. Downcycling was discovered to be a rarity with little to no gains. The only reliable and cheap source of resources for carpet manufacturers are virgin resources.

After the manufacturing process, carpet tiles are shipped to the customer. These carpet tiles last roughly 10-15 years before needing replacement. Upon replacement, carpets are sorted at recycling centers or are directly returned to the supplier. Consumers are to hand over their used carpets at governmental recycling plants. Here, the carpets are mixed with high value recyclable sources like (intact) clothing. At a remote sorting station, these carpets are separated from the higher value fabrics and are sent back to the recycling plant for disposal.

There are three options identified for disposal within the Netherlands. The first disposal method is widely considered a downcycling method in the literature: using nylon fibers to strengthen concrete (FRC). This study discovered that FRC has an even bigger landfill potential than carpet tiles. Creating FRC is just delaying the disposal effects. The second disposal method identified through the literature is incineration with energy and heat regeneration. Compared to common household waste, carpets release twice as much energy upon incineration. The Dutch waste incineration plants are unfit to deal with this increased heat and energy, fearing the structural integrity of their incineration plants. They reroute the carpets directly to the third disposal option: landfilling. This results in an open-ended supply chain: carpet tiles are created from virgin resources and at the EOL they are disposed of in landfills.

What are the environmental costs of one unit of carpet tile, and how much energy is required by the logistical chain?

Based on the findings of the previous sub-question, the following costs of carpet manufacturing and processing was identified:

Table 24

Current costs of one carpet tile (0.25m^2) from cradle-to-grave

	Production		**Shipping**		**Disposal**	
	Virgin resources	Manufacturing	To customer	From customer	Landfilling	TOTAL
kg CO_2-eq.	3.6	0.2	0.1	0.1	0.8	4.9
MJ	72.0	3.5	1.3	1.1	0	78.0
mg PM_{10}	0	11	5	4	0	20

It was identified that the entire supply chain for the production of one carpet tile destined for the Dutch market results in 4.9 kilograms of CO_2-equivalent emissions, requires 78.0 megajoule energy and produces 20 milligrams of particulate matter. Through landfilling, 63,5 megajoule of gross energy requirement in resources is lost.

What options are available to establish a sustainable supply chain?

Some means were identified that would aid the establishment of a sustainable supply chain. These focus on three main areas where resource leaks occur. These areas are the production process, the transportation process and the waste process. The following sustainability increasing measures were identified:

Table 25
Solution space

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	Zero Emission manufacturing	Zero Waste manufacturing	Zero Emission recycling	Zero Emission resources
TRANSPORTATION	Relocation production facility	Zero Emission transport	Decentralized EOL collection	
WASTE	Incineration	FRC	Insulation	Full circularity

It was identified that zero emission manufacturing and recycling cannot be achieved, as even renewable energy sources cause emissions up to some extent (e.g. during the production of a windmill). Even with these emissions, switching from natural gas to renewable energy sources is estimated to yield high gains at a low cost for the industry. Due to the nature of fabrication, zero waste carpet tile manufacturer was deemed too costly to achieve. The mining of resources without producing any emissions was only deemed achievable in a fully circular scenario and is thus deemed impossible in the near future.

For the transportation aspect of the supply chain, it was discovered that the relocation of the production plants could greatly lower the average shipping distance, thus effectively reducing the transportation costs. Adaptation of alternative fuel vehicles, like hydrogen and battery powered trucks, was discovered to only marginally decrease emissions, at the cost of high uncertainty and risk. A decentralized collection plan, in which all carpets are more efficiently collected at local governmental recycling plants, was found to be the most effective and efficient alternative to decrease transportation costs.

Waste reuse/disposal proved to be a difficult issue. The best-in-class alternative, full circularity, was deemed unachievable and too costly in terms of monetary effects. Usage of nylon fibers in FRC caused only marginal savings but increase the landfill potential as FRC is non-recyclable and of much larger volume. Incineration with energy regeneration is the only alternative disposal method to landfilling but sees an increase of particulate matter emissions by almost 50%. It must be noted furthermore that current

Dutch waste incineration plants are unfit to process carpet. The final downcycle option was found in using nylon fibers as insulation material, replacing rockwool. This option looks promising, but the exact properties of nylon as building insulation materials are unknown. Furthermore, this still requires the backing material, roughly two thirds of the carpet tile's total weight, to be disposed.

It can be concluded that with the current manufacturing process and carpet tile composition, no cost-effective sustainable supply chain can be established. Altering the material composition to a backing material that is more easily recyclable fixes this issue, but that does not provide a sustainable solution to the 1.8 billion square meters of carpet that are to be processed in the following ten years.

What is the effect of reverse logistics on the supply chain, and how can this be used to improve the sustainability?

The isolated transportation effect of reverse logistics on the costs of the entire system are slim. Eliminating any RL shipping movements results in a decrease of 2% of GWP and a decrease of 1% of energy requirement. PM_{10} emissions are limited by 22% in this scenario. However, this effect goes beyond the mere transportation costs.

In order to justify a reverse logistics operation, there needs to be an end use for the collected material. In the case of EOL carpet tiles, this is one of the key issues. No market is currently established for EOL carpets, as the recycling of these carpets yields little gains at high costs. Carpet manufacturers have been reclaiming carpets from customers, but these end up scattered across the globe in storage as there is simply no use for these carpet tiles. If this market is ever established, an effective reverse logistics policy could positively impact the total emissions of the system.

One of the hinted markets that is to be established is the housing insulation market. Nylon was identified to theoretically be able to replace rockwool as insulation material. For a carpet tile to become insulation material, the separation of nylon from the backing material is required. This is a relatively easy process and requires a basic shredder. The optimal emissions savings are achieved by supplying local recycling plants with these shredders, thus limiting the reverse logistics distance. The separated nylon fibers can then be locally sold to construction companies which would for instance air-blast these fibers into cavity walls using basic machinery. This also compacts the material for disposal, requiring a better utilization of the transportation volume.

What are the success and failure factors to a sustainable supply chain, what policy is required to guarantee its success, and is governmental intervention needed?

Through the literature study and discussions with members of the industry it was discovered that there are five primary factors that indicate the likelihood of acceptance of any sustainability increasing measure. These factors relate to resilience, financial stability, logistical effort, global image and a limitation of emissions. According to these factors, an alternative that uses zero-emission manufacturing processes, local (decentralized) collection of EOL carpet tiles and reuses EOL carpet tiles for insulation purposes is the most likely to be accepted. Three uncertainties arose when considering implementation of these measures. These were found to be market, costs and ownership.

Without a market, a place where the EOL resources are traded, a demand is not matched to the supply. Currently, the lack of demand and uses for EOL carpet tiles indicate the underlying problem. Nylon is assumed to be too expensive for insulation purposes, which could be a false assumption. This indicates the possibility to establish a market for EOL carpets. How realistic this opportunity is in case of insulation downcycling is to be further explored in a future study.

For this market to be established, a financial injection is needed. However, without clear definition of responsibility, it is unclear who will finance this establishment of a market. The government already indicated willing to finance any sustainability increasing measures. But by doing so, the carpet industry is not (financially) incentivized to produce more environmentally sustainable carpets. This directly relates to the third, and most defining conclusion, an uncertainty of problem ownership.

Carpets are notoriously hard to recycle. If the industry were to be responsible for this recycling, an added incentive is provided to make their carpets more easily recyclable. In the current system, a carpet manufacturer is not responsible for its EOL product. For consumer quantities, the government facilitates free disposal at governmental disposal sites, making for an unjust shift in ownership. The end-user, be it the consumer or the government, is the one carrying the costs of the inability by the carpet industry to produce a product which is more easily recyclable. And with landfilling being the cheapest disposal method, a lot of exhaustible resources are lost. To counter this, two policy adaptations are advised which are derived from currently well-established recycling industries. For consumer quantity carpets, a deposit ("statiegeld") system is advised for carpets, which will ensure that the consumer is incentivized to return the carpets for downcycling. For larger, commercial/industrial, projects, a leasing construction is advised that ensure the carpet manufacturer remains owner of the carpet tiles.

Governmental intervention is required to assign the ownership of EOL carpet tiles to the carpet manufacturer. Only through regulations and taxes a shift in ownership can be achieved. But the government also has vast resources that could aid, or even prove invaluable, in the establishment of the market.

8.2 GENERAL CONCLUSION

Given all the insights in the sub-questions, the main research question can be answered. This research set out to design a sustainable supply chain for the Dutch carpet industry by the year 2030. This research concluded that the best option to increase the sustainability of the carpet tile industry is to facilitate decentralized collection of EOL carpets, use a zero-emission production method (mostly through using renewable energy sources) and by reusing EOL carpet tiles as an alternative for rockwool insulation. Current alternatives, like the current reverse logistics processes and the downcycling of EOL carpets to fiber reinforced concrete are ill-advised as these measures are deemed counter effective. This study is however left to conclude that, based on the findings, a sustainable carpet industry by the year 2030 cannot be created, due to the inability to process the current and future EOL products. The costs of carpet recycling are simply too great.

To achieve a fully sustainable carpet tile manufacturing process, a few major changes are required. First, the carpet manufacturer needs to remain the owner of the carpet tiles. This ensures that carpets are recycled for reuse instead of disposed. Secondly, the manufacturing process needs to be adapted to make carpet tiles more easily recyclable. As these adaptations take some time, and the carpet tile’s lifespan is at least ten years, a sustainable supply chain by the year 2030 was deemed unachievable. And although policy measures could ensure the establishment of sustainable carpet production in the future, the issue of the EOL carpet tiles that are currently on the market cannot be fully resolved. This research identified a construction to limit the emissions and energy requirement of the current supply chain by roughly 30%, deemed the highest available increase in sustainability given the current material composition and production method.

8.3 FUTURE RESEARCH RECOMMENDATIONS

As this research is the first of its kind, some areas are simply left untouched, unproven or otherwise incomplete. This section is aimed at identifying areas where opportunities lie to further expand the knowledge in regard to carpet recycling. The following studies would fit the findings of this study:

Recalculation of effects with the cooperation of the industry

This study was carried out without the cooperation of a carpet manufacturer. This means that many details, like the average shipping distance, production energy requirement etc. are estimates. A cooperation with the industry would be beneficial to substitute these estimates with actual user data. With a large source of uncertainty eliminated, better KPIs can be created that measure the system performance better. Units as emissions gained per unit capital spent can be created, which would be meaningful to the management of these industries, aiding the acceptation and adaptation process. This study's framework is built to be adaptable to suite this new data.

Material study

The recycling of carpet tiles to insulation was advised as it is one of the more effective ways to reduce the landfill potential of carpets. Within the literature, it was identified that nylon could be suitable for (heat) insulation, but no real case studies were discovered. A material study is required to measure how effective EOL carpet tiles are at heat insulation, what materials can be used for insulation, and at what costs the application of these materials comes. If for instance the entire carpet tile can be reused for insulation purposes compared to only the nylon fibers, the benefits to the sustainability would be even higher. But this is just speculation at this point as no studies are found that examine the heat-insulation properties of carpet tiles as building insulation.

Investigate local sources of downcycled material, supply, demand and economies of scale

Through this study, only one source of downcycled material for the production of carpet was identified. Interface uses EOL fishing nets out of the Philippines to create new nylon. The costs of this operation were deemed excessive. This however did raise the question: are there local supplies of EOL product to be found that could be downcycled, or better yet, upcycled, to create carpet? Besides this local source of resource supply, another topic that requires more investigation are the effects of an economy of scale on the calculated effects. No effects of economies of scale were observed and thus modeled. Equally unknown is the supply and demand for certain products. This study assumes that all collected carpets are recycled into the identified uses, but it is possible that there is more carpet created than a single industry can process. This could lead to market failure and is thus advised to study in greater detail.

Dutch incineration plants and carpet waste

Dutch waste incineration plants are unable to process carpet tiles. Yet the literature suggests that carpet tile incineration with energy regeneration is a common alternative to landfilling. These Dutch waste incineration plants cannot process the increased energy emission from the burning of carpets. A future study is advised to discover why exactly Dutch incineration plants are unfit for carpet recycling, and how these can be adapted to accept carpets as feed for the furnace. This study is to include the costs and time aspect of this adaptation.

Detailed supply chain representation

This study failed to include a full actor overview with all interests and powers. This means that an accurate supply map, indicating all suppliers, contractors, shipping distances, routes, modes, warehousing etc. could not be established. Due to corporate secrecy this is a highly complicated task. It would however be beneficial to this study, as it would widen this research notably. With a correct and well-established actor overview, more interdependencies on subcontractors can be modeled. This could alter the results of the MCA dictating the implementation likelihood for other sustainability increasing measures.

8.4 REFLECTION

In this section a personal reflection is presented on the different facets of this thesis. It will present an evaluation of the general process, the created model, designed solutions and on the policy formulation. This reflection discusses what is learnt in these processes and may be a guide to others when replicating this study or conducting a study in a similar fashion.

8.4.1 Reflection on general process

Even though I am very happy with the end result of this thesis, I still think it would have benefited greatly from a (full-time, in house) cooperation with the industry. Data gathering was one of the more complex aspects of this study, and internal information from the carpet industry would have greatly aided the establishment of the model. Of course, this cooperation was sought, well in advance of the start of this thesis. But negotiations took a long time and the industry appeared to be hesitant to allow me to investigate their sustainability. When, on top of that, the COVID-19 pandemic hit, priorities shifted for the carpet manufacturers and the negotiations on a cooperation hit a dead-end. In hindsight, this might be due to the fact that the industry did not want a student poking around in their failing policy, and publicly publicizing these findings. I was stonewalled by some manufacturers, but this is not at all a bad thing. Although extra time had to be spent on processes like discovering the energy consumption of a carpet manufacturing machine, it did provide me the ability to formulate all findings without any type of censorship. I did not have to “please” an employer, giving me the freedom to explore some effects that the industry would not have wanted me to expose. It did however increase the uncertainty of all findings, which is a shame. In hindsight, this thesis would have been easier and/or better if a cooperation with the industry would have been established, and I would advise everyone to seek an industry willing to cooperate.

8.4.2 Uncooperative industry

The unwillingness of the industry to cooperate is perhaps one of most defining aspects of this study. When the internship at interface fell through, I turned to other carpet manufacturers. These ignored every single of my many phone calls, voicemails and emails. Even Interface USA failed to reply on the simplest requests per email. The same upholds for the industry representatives. I got promised an evaluation of the model by the branch organization, but this promise was not honored. This was a personal let-down. I would have hoped for bigger involvement and a willingness to cooperate. I am however grateful to the waste incineration industry, the only general industry that seemed willing to help. I contacted the five biggest waste incineration plants, and three replied back. Likewise, I had good contact with US based researchers, but this contact went cold after sending them the material for evaluation. I think this study would have greatly benefited from the cooperation with these professionals, but I cannot blame them for not cooperating. Of course the COVID pandemic has proven a difficult time for everyone, but specifically for the carpet manufacturers, the way they ignored someone offering their help says it all.

8.4.3 Reflection on model

The model as used in this study was designed to be nothing but a tool for this thesis. However, as time progressed and many iterations were made to the model, it became very solid and reliable. And after spending all this time on it, it felt like a waste not to include the model as a part of this thesis (and evaluation). Although simple, the model was deemed to accurately and adequately model the current situation, given some constraints of course. Both the industry and experts in the field seemed very pleased with the model, wanting to play around with it and to study the modeling outcomes. This effect was unexpected and in hindsight could have easily justified the model becoming the main topic of this thesis.

In regard to the model itself, a few lessons were learned during the fabrication and experimentation. Looking back, creating this model in a dedicated systems dynamics tool, for instance VenSim, would have made programming easier and the model less cluttered. However, in aims of providing a low threshold model for others to use, I still stand by my decision to model the supply chain in Excel.

The modeling results display emissions and energy requirements expressed per carpet tile. This is purposely done to compensate for the lacking exact data. Although this yields the most valuable information to this thesis, it also feels somewhat counter-intuitive. An increase of transported weight does not, for instance, lead to increased shipping emissions whereas this is expected. Of course, any increase in weight equals an increase in carpet tiles, and with an even distribution of this emission across all tiles, the effect is still the same. I would have loved to list the emissions/costs per year or per day of production, but there was simply not enough data to create such figures.

Reflecting on the construction of the model, I have concluded that it was perhaps built too rigidly. There are many user inputs to the model that require an exact data input. This does not model uncertainty accurately. This uncertainty is expressed in the sensitivity tests, but due to the chosen tool (Excel), this sensitivity is not as elaborate as it could have been with other modeling tools' built in validity tests.

For a change in environment, the model needs to be adapted through remodeling. This was a careful balancing act between making an all-encompassing or user friendly model, and the model ended up being a bit of both. It is deemed thus somewhat unfit for use in the far future, but since the aim of this study included a ten year timespan, the model was also not built to calculate effects fifty years from now.

8.4.4 Reflection on created solutions

Oddly enough, I expected more exciting, technological measures to be discovered that could aid the establishment of a sustainable carpet industry. I knew on forehand the difficulties on recycling carpets, but I did not anticipate only finding solutions that have been available for many years. This is largely due to the system demarcation, an implementation time of less than 10 years does not facilitate highly futuristic technologies. But that also reflects reality. Futuristic alternatives do not offer a solution to the current problem and are thus not prioritized.

8.4.5 Reflection on policy advice

The policy advice was the most surprising aspect to the study. I found that the root of the problem was a lack of stimuli for the industry to manufacture sustainable carpets. A shift in ownership and responsibilities was discovered to be one of the mechanisms to increase sustainability, more so than any technological breakthrough I had envisioned. Analogies were vital in the creation of a policy advice and could have expanded more. Unfortunately, due to time constraints, these analogies are not discussed to the amount of detail that I would have liked. Likewise, other analogies could have possibly provided new insights, like PVC or metal recycling.

8.4.6 Reflection on the main findings

I was surprised to find that the most uncertain alternative to downcycling/recycling, the usage of EOL nylon fibers for building insulation, proved to be one of the best alternatives. Studies indicate that nylon was long deemed too expensive for this purpose, but all current sources contradict this. It is however a largely unproven downcycling method and requires further investigation. This is beyond the scope of this research, and perhaps even the capabilities of the student. I am very interested in the outcomes and hopeful this will be picked up for future research.

I expected the industry to have a dislike for my policy advice to make them responsible for the EOL product through leasing constructions. However, during the validation with an industry representative, it became obvious that this scenario was already being explored by the industry. There seems to be a general awareness that the carpet industry cannot keep functioning like it currently does, and the industry is already thinking ahead. I am hopeful that this study will contribute to this thinking ahead and aids in the establishment of a sustainable carpet production industry.

8.4.7 Lack of stakeholders

An expanded stakeholder analysis is something that is absent throughout this study. Early on it was identified that the government and the industry themselves are the main stakeholders and have the most invested interest and power to affect the system. This however does not mean that other actors and stakeholders are not able to increase the sustainability of the entire supply chain. Simply due to time constraints, there is a distinct lacking of consideration for other stakeholders other than the industry and the government.

This thesis could have benefited from the creation of a full logistical map, including all subcontractors, specifics on resource origins, shipping methods, distances, storage etc. This data was however extremely difficult to find, as corporate secrecy (as discussed earlier) plays a major role when looking for data. It felt like this could have become the topic of a full study by itself due to the scarcity of data, with a route optimization problem that would inevitably follow. The difficult decision was made not to include this high-detail supply map in the late stages of this study, simply due to time constraints and other prioritizations. The aggregate level of this thesis is of such a level, that I feel like this choice is justified. A highly detailed actor analysis would not have changed the main findings of this study, other than add a new level of detail to it.

8.4.8 My contribution to the body of established knowledge

This study identified multiple knowledge gaps in terms of sustainability increasing measures that are available to the Dutch carpet industry. By far the biggest contribution to the body of academic knowledge is the discovery of building insulation as a possible EOL carpet tile downcycling use. It further expresses the costs of carpet production for the Dutch welfare, which is unachieved prior to this thesis.

This study established a framework that generates sustainability increasing measures, evaluates their effectiveness and scores these on their likelihood of adaptation. Besides this framework, an unambiguous overview of the current industry was created, it was identified where opportunities arise to increase the sustainability of the carpet industry and by what means this sustainability can be increased. A new way to downcycle carpet tiles was identified, which is not yet properly explored by academics. With the aid of analogies, it was discovered that the carpet industry could benefit from a product-service system, which by itself is not a new concept, but was not linked to the carpet industry prior to this study.

9 REFERENCES

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Van Harmelen, A. K., & Koch, W. R. R. (2002). CO_2 emission factors for fuels in the Netherlands. *TNO, Apeldoorn*.

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Vogels, P. (2019, November 27). Tweed eleven voor oude tapijttegels: Desso in Waalwijk recyclet straks voor heel Europa. *Brabants Dagblad.*

Vreuls, H. H., & Zijlema, P. J. (2009). The Netherlands: list of fuels and standard CO_2 emission factors. *SenterNovem report to the Ministry of VROM (Spatial Planning, Housing and the Environment, Utrecht, the Netherlands*.

Wang, Y. (1999). Utilization of recycled carpet waste fibers for reinforcement of concrete and soil. *Polymer-Plastics Technology and Engineering*, *38*(3), 533-546.

Wang, Y., Cho, B. S., & Zureick, A. H. (1993, October). Fiber reinforced concrete using recycled carpet industrial waste and its potential use in highway construction. In *Proceedings of the Symposium on Recovery & Effective Reuse of Discarded Materials & By-Products for Construction of Highway Facilities, Denver, CO* (pp. 4-111).

Wietschel, M., Kühnbach, M., & Rüdiger, D. (2019). *Die aktuelle Treibhausgasemissionsbilanz von Elektrofahrzeugen in Deutschland* (No. S02/2019). Working Paper Sustainability and Innovation.

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APPENDIX

A LITERATURE STUDY

A.1 LITERATURE STUDY

As for this research to be supplement to the current academic knowledge, an extensive literature review was carried out in order to ensure no similar solutions already exist for this specific sector. In the search for literature databases as Springer, Emeraldinsight, ProQuest, ScienceDirect, Sagepub and the TU Delft online library were used amongst others. During the initial literature research, a new core concept was identified. This caused a shift in research and ultimately led to the identification of a knowledge gap. The next paragraph will discuss these (initial) findings.

These articles were reviewed:

Table A1

Literature research articles: suggested ways to improve sustainability

Author(s)	*Year*	*Area*	*Main topic*
Shaikh	*2009*	Reduce water usage	*Dyeing process*
Miraftab, Horrocks & Woods	*1998*	Reduce waste	*Alternative uses for discarded carpets*
Peoples	*2006*	Reuse carpets	*Limited potential for discarded carpets*
Capar, Yetis & Yilmaz	*2006*	Limit toxicity water	*Printing technologies*
Chinnasamy, Bhatnagar, Hunt & Das	*2010*	Reuse wastewater	*bio-fuels*
Cline, LeMay & Helms	*2015*	Reverse logistics	*Diverting old carpets from landfills.*
Kant	*2012*	Environmental	*Dyeing process*
Olthaar, Kral and Lunenborg	*2017*	Circularity	*Resource leaks*
Nelson	*2009*	Innovation	*Using EOL products from other industries*
Rosenberg	*2009*	Innovation	*Using employer, bottom-up, participation to create sustainability.*

In the initial search for improving sustainability a wide range of (technical) solutions were discovered, mostly aimed at the production stage. In the coloring of carpet traditionally a lot of water is used. Wasted even, as some experts argue (Capar, Yetis & Yilmaz, 2006). Shaikh concluded in 2009 that by using a new form of dying, 70% less water could be used in the coloring process of carpets. And the remaining contaminated water could then be transformed into biofuels (Chinnasamy, Bhatnagar, Hunt & Das, 2010). Kant (2012) argues that the coloring process of any fabric is a highly toxic and environmentally harmful process. They all argue for new technological processes to reduce the environmental impact of coloring fabrics (Capar et al, 2006; Chinnasamy et al., 2010; Kant, 2012).

A second school of thought focusses not on the dying and production, but on the end-of-lifecycle product. To mitigate the environmental impact of the production of carpets, they claim the key lies within finding a way to deal with the leftover product. Cline, Lemay & Helms (2015) concluded that there was a positive trend happening that diverted old carpets from landfills. However technological advances were deemed necessary to recycle carpets within the carpet industry itself. This complied with the findings of Peoples (2006) and Miraftab et al. (1998), that found recycled carpets to only have a use outside of carpet production. Following this thought, it can be concluded that there is some sort of a market for discarded carpets. Cline et al. (2015) continued the analysis by concluding that a good infrastructure was needed to facilitate reuse, allowing the establishment of a reverse logistics system. Interface flooring has been focused on limiting the environmental impact since 1998, and has come up with a way to reuse leftover material from other industries (Nelson, 2009) as well as heavily relying on the workforce to come up with measures that limit waste (Rosenberg, 2009). With the insight that used carpets have some degree of value, but are still being discarded in landfills, it made for a shift of focus towards the logistic value of one unit of carpet tile. Apparently there are applications for reusing carpets that remain unused due to factors unknown, as one of the world leaders primarily focusses on reusing other products and limiting waste. In that, a new core concept was found: resource leaks.

A.2 CORE CONCEPTS

After the preliminary literature study, a few concepts arose on which the following literature study will continue. These concepts were reverse logistics, closed-loop production/circularity and resource leaks, which are in the carpet industry all closely linked to one another. The concept of reverse logistics was introduced by Cline et al. (2015). This includes the logistic process of returning goods to the manufacturer. For the carpet manufacturer, this process aids the second core concept: the closed-loop production. In a closed-loop production process, no virgin resources are used to create a product. In the case of the carpet industry, this would mean that old carpets are transformed into new carpets. This would ensure sustainability and is estimated to severely limit the emissions (Cline et al. 2015). In literature, this is considered a part of circular economy, or “circularity” in short. The third concept is resource leaks, which is a concept established by Olthaar, Kral and Lunenborg (2017, October) and describes a process in which processed materials lose their logistic value in the chain.

A.3 MAIN FINDINGS

Table A2

Literature research articles: Reverse Logistics in carpets – difficulties and possibilities

Author(s)	*Year*	*Area*	*Main topic*
Wang, Cho & Zureick	*1993*	Reused carpets	*Fibers to reinforce concrete*
Helms & Hervani	*2006*	Lack of demand	*Limited uses for carpets*
Realff, Ammons & Newton	*1999*	Production process	*No reverse production systems for carpet industry*
Biehl, Prater & Realff	*2005*	Recycling market	*No match in supply and demand*
Kinobe, Gebresenbet, Niwagaba & Vinnerås	*2015*	Reverse logistics	*Importance of reverse logistics is underestimated*
Fleischmann	*2003*	Reverse logistics	*Logistics network design important for closed-loop supply chains*
Sharma, Panda, Mahapatra & sahu	*2011*	Barriers in reverse logistics	*Return logistics as a service*
Louwers, Kip, Peters, Souren & Flapper	*1999*	Reverse logistics	*Facility location model*
Agrawal, Singh & Murtaza	*2015*	Reverse logistics	*Literature study*
Hosseini, Chileshe, Rameezdeen & Lehmann	*2014*	Construction industry	*Construction industry not aware of benefits reverse logistics*
Sobotka & Czaja	*2015*	Resource management	*Reverse logistics advised for decision making*

While concluding that there are several uses for recycled carpets, the collection of said carpets is identified as being problematic, as well as the lacking demand for these carpets. But the overlapping issue is that somewhere in the chain, carpets lose their value for being recycled into new carpets. This results in the fact that only 1% of all carpets are being recycled (Helms & Hervani, 2006). Both Fleischmann (2003) and Cline et al. (2015) indicate that a well-established reverse logistics process is necessary to improve this, ultimately seeking full circularity. This adaptation of a reverse logistics process entails everything from how to collect the reusable carpets to the re-distribution and the cost/benefits of recycling old carpets. The economic theory suggests that clever reverse logistic structures are a good way to manage returns cost effectively (Winkler, 2011). Furthermore, the closed loop production theory is identified as a great tool to ensure sustainability (Winkler, 2011). It is argued that returning old carpets to the supplier is not only a way of providing a service (Sharma, Panda, Mahapatra & sahu, 2011) but it could also create economic gains for the company (Kinobe, Gebresenbet, Niwagaba & Vinnerås, 2015). It is argued that the construction industry is not aware of the (ecological) advantages of reverse logistics, and consequently that poor management causes bad resource management (Hosseini, Chileshe, Rameezdeen & Lehmann, 2014; Sobotka & Czaja, 2015). It is also argued that there is a lack of demand for used carpets (Helms & Hervani, 2006) and that this is one of the main issues in achieving circularity within the industry (Fleischmann, 2003). A well setup (logistical) infrastructure is required to effectively facilitate the reuse of carpets (Cline et al., 2015) and this is currently one of the major issues (Helms & Hervani, 2006; Realff, Ammons & Newton, 1999; Biehl, Prater & Realff, 2007). In all, it can be concluded that there are possibilities to strife for a full closed-loop production system, as long as there is any value left in EOL carpets. When unwanted/EOL carpets do not have the ability to provide resources for the production of new carpets, there is no use in returning the carpets to the manufacturer and circularity will not be achieved. For this, insight must be gained into the basics: where in the process do carpets lose their logistic value, and how can this be regained?

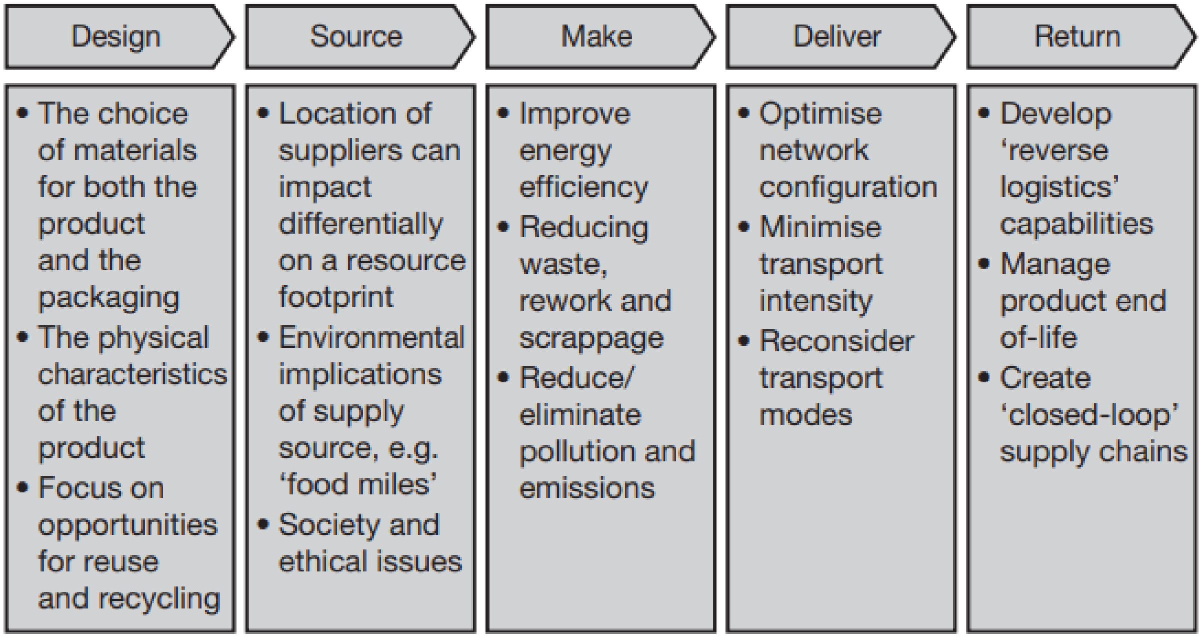
A.4 LITERATURE LIST

As the concepts of reverse logistics and circularity are relatively new to the carpet industry, information proved to be scarce. Much effort went into finding, and combining, sources to create a coherent overview of the system. This was particularly true for the creation of the model, where many different sources only described a very small part of the carpet supply chain. This causes the literature list to be extensive.

B RESEARCH FRAMEWORKS AND THEORETICAL CONCEPTS

B.1 SUPPLY CHAIN MANAGEMENT

The first framework that will be used as a guide in this research is the concept of supply chain management. Supply Chain Management is the management of physical product, information and financial processes or flows from production, transportation up to and including inventory, for a producer as well as other suppliers (Ludema, 2008, October). In other words, it describes the process of creating an item, transporting an item, and storing the item until a consumer or otherwise end-used is reached. Ludema (2008) identified Supply Chain Managers as people that "have knowledge of environmental factors that might lead to greening of the supply chain" (Ludema, 2008, October, p.1). In order to achieve this, knowledge of environmental factors is required, as well as oversight on the entire logistical (supply) chain. Within supply chain management, '4Rs' are identified to guarantee a successful supply chain management program. These are Responsiveness, reliability, resilience and relationships (Christopher, 2011). It is identified the growing concern for the environment has led to a shift in supply chain management, where sustainability has become one of the key design principles. Christopher (2011) identifies sustainability in three P's: planet, people and profit. These are however interlinked, as a better routing could also lead to financial profit for the company. And in this lies the crux: the main goals are to ensure continuity of business and viability, and as long as sustainability adds to this, it is a great tool. But if, in turn, it makes the entire logistical process unviable, an adjustment to the logistical process is required. For this, Christopher (2011) developed the following model (Christopher, 2011, p.248):



Design	Source	Make	Deliver	Return
• The choice of materials for both the product and the packaging • The physical characteristics of the product • Focus on opportunities for reuse and recycling	• Location of suppliers can impact differentially on a resource footprint • Environmental implications of supply source, e.g. 'food miles' • Society and ethical issues	• Improve energy efficiency • Reducing waste, rework and scrappage • Reduce/ eliminate pollution and emissions	• Optimise network configuration • Minimise transport intensity • Reconsider transport modes	• Develop 'reverse logistics' capabilities • Manage product end of-life • Create 'closed-loop' supply chains

Figure B1. Supply chain decision framework (Christopher, 2011, p.248)

Supply chain management establishes a framework for policy in terms of viability and efficiency. In figure B1 it shows how supply chain decisions impact the resource footprint. In the return flow column, it states that reverse logistics capabilities are to be developed, as well as end-of-life product management as well as the creation of closed-loop supply chains (Christopher, 2011). These principles are reflected in the mission statements of both Interface and Tarkett/Desso and appear to play a key role in reaching sustainability. The fact that carpets mainly end up incinerated or in landfills are a clear indication that this return process is simply underrepresented in the supply chain management of carpet tiles. For this reason, each of these concepts will be discussed individually as a framework, in order to close this final gap in establishing a sustainable supply chain.

B.2 REVERSE LOGISTICS

Reverse logistics is, quite simply put, the logistic process of returning the end-of-lifecycle item from a consumer to a processing unit, often in order for it to either be repaired or recycled (De Brito, Dekker & Flapper, 2005). Within reverse logistics there are two types of motivation identified: economic and ecological (Fleischmann, Bloemhof-Ruwaard, Dekker, van der Laan, van Nunen & van Wassenhove, 1997). Further distinction is made in terms of criteria for type of recovered items, form of reuse and actors involved. A framework for reverse distribution, the process of returning the goods, was established in terms of forward and reverse channels, and looks as follows (Fleischmann et al., 1997, p. 5):

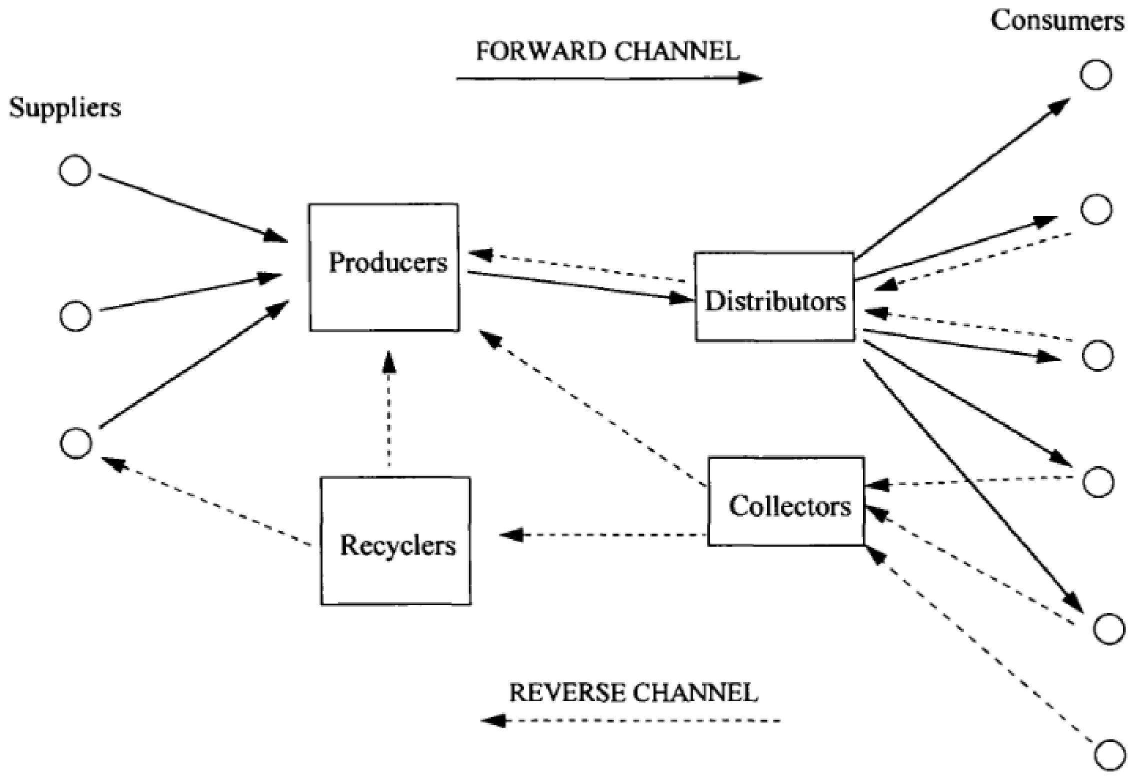


Figure B2. Framework for reverse distributions (Fleischmann et al., 1997, p.5).

Important to note is that the reverse logistics process is not a mirrored image of the forward distribution process. It can adapt a vastly different (logistical) path. It was identified that the required transportation for the return flow was a decisive factor in the overall ecological impact of the supply chain (Fleischmann et al., 1997).

B.3 CLOSED LOOP PRODUCTION/CIRCULAR ECONOMY

Once the carpets are returned to a processing unit they can either be recycled, upcycled, downcycled or disposed. The following table, (Table B1) tries to explain in the main advantages and disadvantages of each of these options:

Table B1

Advantages and disadvantages of recycling/downcycling/upcycling/disposal

Type	General description	Pros/Cons	Example
Recycling (according to Mihut, Captain, Gadala-Maria, Amiridis, 2001)	Creating a new product or material of similar quality from waste product	+ No or less virgin resources used in production - Processing of waste often required	Printing a newspaper on recycled old paper
Upcycling (according to Vadicherla & Saravanan, 2014)	Creating a new product or material of better quality, increasing environmental value	+ Offset environmental strain, added value to new product - Repurposing might be costly	Make a carpet out of EOL nylon fishing nets
Downcycling (according to Vadicherla & Saravanan, 2014)	Creating a new product or material of lesser value and functionality	+ Resources diverted from disposal - Value lost through downcycling, possibly loss of incentive for seeking circularity	Make a carpet out of fabric leftovers of the clothing industry
Disposal (according to Xu, Tang, Shang & Zhao, 2010)	Getting rid of the product by either destroying or (semi-permanently) storing.	+ Still some value in power/heat reclamation or composting - Relatively big loss to social welfare	Storing solid waste in landfills, incinerating waste in powerplants or composting waste.

As observed in the title, the current option of disposing carpets is the least favorable option. Through the incineration of carpets, energy or heat is won, but at the cost of emissions. The landfill option simply dumps all waste product in a place without any form of processing. These types of garbage disposal are very unsustainable and thus least preferable.

In an ideal world, used carpets are returned to the factory and are 100% recycled to produce new carpets just like glass. This type of recycling is often indicated with closed-loop production (Modak, Modak, Panda & Sana, 2018), as it eliminates the requirements for virgin resources. This process prevents the loss of (logistical) value of carpets, as it can thus be indefinitely recycled. Examples of successful closed loop industries are the paper industry, glass industry and arguably the plastic industry (Stindt & Sahamie, 2014). Within circular economics, as defined by ISO 14044, a closed-loop production system may only require input of equal value and from an identical product, as it defines closed-loop as "material from a product system is recycled in the same product system" (International Organization for Standardization, 2006). On the contrary, open-loop production processes such as the industry's current standards, are considered the least desirable options for circular economies (Deschamps, Simon, Tagnit-Hamou & Amor, 2018). It can thus be concluded that recycling either through downcycling or upcycling might be ways to increase the circularity, it goes against the principles of closed-loop production processes (Haupt, Vadenbo & Hellweg, 2017). This distinction must be kept in mind when considering the aims and desires from the industry, as it might indicate a miscomprehension of the definition of closed-loop production.

There are however a few conditions that have to be met in order to achieve full circularity. And with that, the question arises what the main goal should be. Circularity can often be increased in numerous different ways. However, the costs of reclamation are an important factor to consider, both environmentally and financially. If for instance a polymer can only be recycled through chemical recycling and the waste product is a highly toxic or chemical waste product without any use, the aims of achieving a closed-loop resource flow comes at a high cost. This is covered in the framework by De Brito et al. (2005).

De Brito et al. (2005) discovered three types of constraints in closed-loop supply chains. These are inaccessible EOL products, lacking technical or economic feasibility for recycling and/or no market for the secondary resources gained through recycling. The following figure is used to describe this relationship (Brito et al., 2005, p.204):

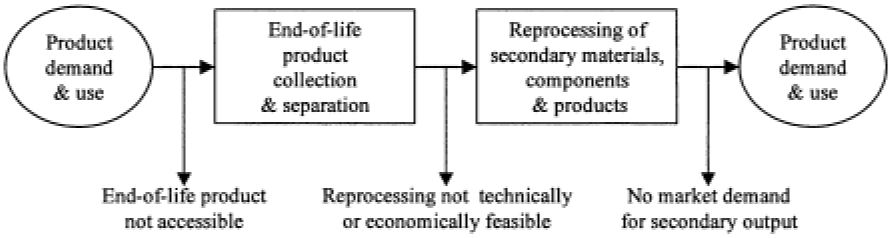


Figure B3. Constraints in closed-loop supply chain framework (Brito et al., 2005, p.204).

These constraints must be kept in mind when designing a circularity model. Whenever a scenario arises in which one of these three bottom situations occur, it heavily impacts the circularity of the whole supply chain. This framework will then be used in the rating of policy measures (chapter 7) to test the solution on various scenarios.

B.4 VALUE CHAIN MANAGEMENT

Within the classic supply chain approach, no thought is given to the EOL product (Govindan & Soleimani, 2017). To fix this, somewhat contrary to supply chain management, in which a heavy focus lies on the costs of goods, value chain management focusses on the consumer first. It describes the process of adding value to a product in the eyes of a consumer by relying on innovation, marketing and social trend analysis (Feller, Shunk & Callarman, 2006). This Value Chain Management (VCM) is then sometimes also considered an extension of Value Chain Management (Al-Mudimigh, Zairi & Ahmed, 2004). This consumer focus allows for cooperation between different industries and organizations in order to achieve increased value. This can for instance be providing service to the customer by collecting and returning the used carpet tiles to the factory and is traditionally outside the scope of resource management principles. Incorporation of VCM principles allows for better adaptation of solutions, as it is a tool to assess the probability of adaptation by the public.

B.5 RESOURCE LEAKS

Resource leaks is a theory as described by Olthaar et al. (2017, October) and discusses the unnecessary loss of resource value. It occurs when either resources are not recycled at the EOL, are downcycled to lower value goods, or when the recycling requires a large amount of supplement resources like water or energy (Olthaar et al., 2017, p.3). It then goes on to describe a pool of possible causes of resource leaks, and types of identification. One indication of resource leaks is for instance when the production requires more resources than are available in the end product (Olthaar et al., 2017, October). Following this line of thought, it can be concluded that resource leaks can occur anywhere in the value chain, including at the end of collection. This, in line with full circularity, means that one unit carpet tile should be fully recyclable into one new unit of carpet tile, of equal value, if no resource leaks occur. When the recycling effort takes more than one unit of EOL carpet tile to produce one new tile circularity might be achieved, however in sights of resource leaks, there is still value lost in the carpets and effort should be put in to prevent this loss of value. Many sources of resource leaks have been identified to occur in the manufacturing process (Olthaar et al., 2017, October). A zero-waste manufacturing approach could prove to be very insightful and is currently also the main academic focus for the carpeting industry. However, as the main focus of this study lies on the logistical knowledge gaps and uncertainties, this production-focused approach is mostly neglected throughout the study. It instead focusses more on the closed-loop supply chain theory, which was identified by Olthaar to mainly cover resource leaks that occur during the reverse logistics (Olthaar et al., 2017, October, p.5).

C MODEL CONSTRAINTS & FUNCTIONALITY

This appendix discusses the requirements of the research and model through a MoSCoW methodology. This means that a list is presented that contains the must have functions of this model, the should have features of the model, the could have features and finally the will not have features. These tables include a source of the functionality, where it was based or originated from, and will be briefly elaborated why this is either included or excluded.

C.1 GENERAL CONSTRAINTS

The first constraint is that the modeling results should be within the realm of possibilities. Meaning a negative emission (thus absorption of GHGs) or negative energy consumption (producing energy) during the carpet's lifespan is deemed unlikely and unrealistic. Likewise, emissions and energy requirements of any sustainability increasing measure that exceed the original situation by a significant amount are excluded from consideration as they do not attribute towards reaching the goal. Note that the term significant amount is used somewhat ambiguously. There is still a window of tolerance for increased emissions or energy requirements in order to achieve greater sustainability, for instance in the establishment of a fully sustainable resource supply.

The second constraint is in terms of accuracy of the model. If the model cannot accurately and realistically simulate the current situation, any adaptation of the model will result in equally incoherent results. As this study sets a particular carpet tile as the standard (Interface's Touch & Tones 103), the nil-alternative modeling results can be compared to the manufacturer's Environmental Product Declaration (EPD). The EPD is an independently created assessment of sustainability through lifecycle analysis, presenting this sustainability in terms of GWP. As the model aims to calculate the same effects, this facilitates a form of validation. It is vital that the EPD data is not used for the creation of the model, as this would render all validation efforts using the EPD invalid. Thus, the constraint was formed that all modeling data should be from independent scientific sources. In terms of tolerance, the model should not produce results that are more than a 5% deviation of the EPD results.

A third constraint is found in the cost aspect of sustainability increasing measures. The amount of costs should be in proportion to the increase in sustainability. The costs of sustainability increasing measures by the manufacturer should not exceed the revenue of the manufacturer over the lifespan of these measures. In other words: if the purchase price of machinery to produce carpets is more than what it will gather in revenue, the adaptation will become unlikely. There are however limitations to this constraint. This evaluation of cost effectiveness is not entirely up to the manufacturer. Emissions are also considered a governmental problem by the Paris Agreement, making the government a partial problem owner. Through environmental regulations, the government is able to exercise their influence on the industry. Likewise, the government has proven to be very willing to aid the industry in increasing sustainability, even offering to compensate investment costs. This calls for the creation of two scenarios: one in which the industry is responsible for the costs of increased sustainability, the other in which the government will finance these measures.

The final major constraint is time. With the aim of increasing sustainability by the year 2030, any means considered should be achievable within this timeframe. This means that implementation times of these measures should be 10 years or less. More importantly, this limits the solution space by not allowing for any (policy) measures that are not currently available or are not available within the near future. This design does not facilitate in the adaptation of means that are futuristic of nature. The added benefit of this constraint is that it decreases the uncertainty of the presented solutions, but it could also nullify current (research and development) efforts on future sustainability increasing measures.

C.2 MUST HAVE

Table C1

Must have functionality of the model

Must have	Reason	Source/origin
Downcycled resources source stream	Able to incorporate and calculate effects of EOL carpets that are not disposed and when no capacity is currently available to recycle these into new carpets	Lampikoski, 2012; Khoo, 2018
Virgin resources source stream	Carpet production uses a lot of virgin, exhaustive, resources which should be minimized in order to increase the sustainability of the industry	Cline et al., 2015
Product specification	In order to calculate costs of a carpet tile, the exact material composition is to be known, as carpet is a heterogeneous product there is not one type of carpet tile	Nelson, 2009, also based on limitations of treating carpet as homogeneous product.
Shipping stream (manufacturer to customer)	Supplying the customer with the carpets require a shipping effort which create emissions, also an indication of efficiency in terms of routing	Cline et al., 2015
EOL disposal stream	EOL carpet disposal is the main issue, which the model should correctly display in order to calculate the effects of possible resource leak fixes	Cline et al., 2015; Choudhury, 2014; Miraftab et al., 1998
CO_2-equivalent costs overview	CO_2-eq. costs give a straight-forward, easy to comprehend, overview of the environmental costs	Heijungs, 2005

C.3 SHOULD HAVE

Table C2

Should have functionality of the model

Should have		**Source/origin**
Energy source selection	Able to model the difference from producing using sustainable energy sources, which is currently one of the focus points of the industry	DuBose, 2000
Emissions per energy source	Different energy sources have different emissions, which reflect the total emission of e.g. the production process	DuBose, 2000
Closed loop recycling stream	Although deemed impossible by experts, this is the set goal by the industry and thus included to calculate the effect of circularity	Fleischmann, 2003; Cline et al., 2015
Reverse logistics stream	Reverse logistics costs are one of the pillars of emissions that could be reduced by clever policy formulation	Cline et al., 2015
Recycling/ downcycling specification	Different EOL uses have different costs and gains, the model should differentiate between these and model the effects of different EOL solutions	Helms & Hervani, 2006; Biehl et al., 2007; Choudhury, 2014
Productional losses stream	Calculates the effect of zero-waste production, as trimming losses are a noticeable cost in carpet industries	Condor Group, 2020
Selection of methods of transportation	Different shipping modalities have different emissions, which could lead to over- or underestimation of emissions	Cline et al., 2015
Energy costs overview	Besides GHG, energy requirement is also an indication of efficiency	Choudhury, 2014
Usage losses to carpet	Besides the productional losses, through the usage of carpet, material gets lost too. These effects the amount of reusable/disposed product at EOL	Condor Group, 2020
Beeline to km shipping conversion	Beeline distances rarely reflect actual kilometers, causing an underestimation of emissions by 40%	Boscoe et al., 2012

C.4 COULD HAVE

Table C3

Could have functionality of the model

Functionality	Reason	Source/origin
particulate matter overview	Although all environmental effects are to be captured in the CO_2-eq. unit, particulate matter is an environmental effect of a different scale and could be mentioned separately	Guttikunda & Goel, 2013
Fabric coloring costs	The costs of nylon coloring were identified to be very environmentally straining. It can be included, although it is a static cost that will always remain equal as demarcated by this study	Soleimani-Gorgani & Taylor, 2008
Lifespan of carpet	The lifespan of a carpet effects the environmental strain in terms of material requirement and EOL processing capabilities	Fletcher, 2012

C.5 WILL NOT HAVE

Table C4

Will not have functionality of the model

Functionality	Reason	Source/origin
warehousing costs	Costs for warehousing are not included in the model as carpets are manufactured to demand by either the customer or wholesalers, and these costs are not associated with the manufacturer themselves. It requires very temporary storage before shipping which will be neglectable	Ludema, 2008
transshipment costs	Like warehousing costs, the costs of operating a forklift truck in order to load the pallets of carpet tiles onto the shipping modality is not included due to the small significance and the fact that these costs are always present and do not pose a difference compared to the nil-alternative	Ludema, 2008
usage costs (cleaning etc.)	The usage costs of carpet are not included due to the fact that these vary hugely and are not influenced by the industry	Bossenmayer et al., 2019, January

C.6 MODEL SPECIFICATION CONTINUED

This section discusses the must have and should have specifications as listed in chapter 4.2.3. This section elaborates why these specifications are deemed important for the model.

Functions that are deemed to be vital for the operation of the model are discussed in the “must have” category. The very first functionality is the ability for the model to have a separate downcycled resource stream. As discussed by Lampikoski (2012), circularity is the main goal for some carpet manufacturers. Khoo (2018) discusses how current production facilities by Interface are equipped to deal with EOL nylon fishing nets as a source of nylon for their carpet production. This indicate some degree of recycling is currently already embedded into the production facility. Leaving this opportunity out of the model would pose a severe limitation and underestimation of current efforts, and thus is included in the model. Cline et al. (2015) argued for a reverse logistic stream with the function to limit the reliance on virgin resources, just as Lampikoski (2012) increased the notion of circularity. This circularity cannot be made insightful without modeling the virgin resource stream. As discussed earlier, carpets are as heterogeneous as cars: there are different brands with different material/manufacturing processes. Some resources that go into the manufacturing of carpet are recycled (Lampikoski, 2012; Khoo, 2018) and thus will feature a different environmental strain than the resources that are more difficult to recycle. In practice the top layer of a carpet is more easily recycled than the backing material which is more likely to be disposed of. In order to model this effect, product specification (what exact individual resources go into one carpet, or what carpet is modeled) is an important aspect the model should communicate clearly. As discussed by Cline et al. (2015), one of the key components to increasing sustainability for the carpet industry is the establishment of a reverse logistics stream. In this, the shipping route and modality are covered as a tool to increase sustainability. There are currently some reverse logistic processes ongoing as well, and as such they should be modeled. Finally, as discussed by Heijungs (2005), CO_2-equivalent emissions are the benchmark in current literature for calculating GWP. It is thus a given that the model should supply the researcher with data regarding the GHG production of the industry in terms of CO_2-equivalent units when considering sustainability and environmental impact.

What the model should have start off with an energy source. Interface considers any energy that is used that is not produces through renewable sources as waste (DuBose, 2000). This indicates that the energy source is of importance to the industry. The effects of this energy selection are however unknown thus would make for an import feature in the model. Likewise, Bruckner et al. (2014) state that renewable energy sources, even those advertised as zero emission, all cause emissions up to a certain degree. Assuming that all renewable energy sources would pose a zero-emission energy source would lead to an overestimation of the effects, and as such are to be included when modeling the different energy sources as well. While currently not available, many experts argue that closed loop circularity would be the ultimate goal for the carpet industry. Thus, this effect is included in the model in order to estimate the effects of this ultimate goal. Cline et al., argued that an effective reverse logistics process is the first step to increasing sustainability. Current manufacturing processes by Interface and Desso also include a reverse logistic policy. Thus, this policy should also be included, even though sources indicate that these carpets go unused after reverse logistics. Following that thought, the modality of transport is of influence on the total emissions of the supply chain, as some vehicles emit more than others. Then there is the issue regarding what uses EOL carpet have. Helms & Harvani (2006) and Choudhury (2014) argued that there is currently no market for EOL carpets, meaning there are no industries willing to take on the waste product of the carpet industry. Biehl et al. (2007) argue that recycling carpets would cause emissions and cost energy. As this was identified to be one of the major limitations this research set out to tackle, the model should incorporate possible means to downcycle or recycle carpets and specify to which use they will be reused. It must also include means to deal with carpet if it cannot be recycled or downcycled, thus different disposal methods will feature in the model. It furthermore should include the costs of this recycle operation. With that, the Condor Group stated it as one of their goals to produce fully zero-waste, meaning during the construction of a carpet no material is discarded. This goal ensues the zero-waste manufacturing school of thought that limiting productional waste causes less losses. Besides GWP, energy requirements/costs are also discussed as a factor indicating sustainability (Grigoroudis, Kouikoglou, Phillis & Kanellos, 2019) and are thus included as well. Second to last feature the model should have is a control over the usage losses to a carpet. During the lifespan of a carpet some material gets lost through everyday usage. Some fibers might get separated from the backing material or are worn down. The degree of this degradation determines the amount of recyclable resources that are left at the EOL. Totally worn-out carpets have fewer recyclable resources yet pose a lesser environmental strain at the disposal stage. Finally, a conversion factor is to be modeled that translates a beeline shipping distance to actual kilometers. In supplying a customer, the origin and destination is known. Thus, actual kilometers can be entered into the model. When assuming averages and making assumptions on service ranges, the distances are based on beeline kilometers, which hardly represent actual road kilometers (Boscoe et al., 2012). Thus, the model should have a function to compensate for this underestimation of driven distance.

D MEANS – EXPLORATION

This appendix describes the identified sustainability increasing measures which are briefly presented in chapter 4.

D.1 PRODUCTION PHASE RESOURCE LEAK FIXES

During the production of carpet tiles, logistic value can be lost on all different stages and phases. Interface specially designed an improvement methodology using the knowledge of the factory workers in a bottom-up approach to creating sustainability (Rosenberg, 2009). This resulted in solutions like the insulation of several pipes and other parts of the factory (Rosenberg, 2009). This section will discuss means that this study generated to increase the sustainability of the entire chain during the production process.

D.1.1 Zero-emission manufacturing

Through Interface's mission statements (DuBose, 2000) it has become clear that this carpet manufacturer values renewable energy sources highly. As such, a zero-emission manufacturing means is adapted into the model as a possible solution to increase the sustainability of the entire supply chain. This means does however not nullify the emissions of the entire production category. The emissions of this process are built up from resource acquirement, energy requirement during manufacturing and the source of energy. Trying to achieve zero-emission manufacturing means that effort is put into selecting an energy source with the least amount of emissions, thus likely to be generated fully renewable. It also means that an attempt is made to capture all emissions during the manufacturing process, such as heat, (toxic) fumes and particulate matter, and process these by-products fully sustainably.

D.1.2 Zero-waste manufacturing

Where interface's mission statements primary focus on zero-emissions, one of their competitors are focused on another aspect of production: waste (Condor Group, 2020). Especially during carpet tile production, waste is always a by-product of fabrication. In cut pile carpets for instance, all created nylon fiber loops (like the ones depicted in figure 2) are cut to form open-ended fiber strands. This cutting process causes some nylon fibers to be lost (Miraftab et al., 1998). Furthermore, trimmings pose a significant loss to carpet manufacturers, as running meter rolls are supplied and are cut to produce tiles. During this cutting and trimming procedure, material is lost (Miraftab et al., 1998). Following this discovery, one possible means could be to eliminate this waste by improving the manufacturing process. This however edges on being rejected by the constraints due to being unachievable within the timeframe, as it is very likely that manufacturers will have improved upon manufacturing processes to eliminate waste if they could have. However, as Miraftab et al. (1998, p.6) suggested, besides the aid of computer guided production processes, one way to noticeably decrease productional waste is to homogeneous carpets across all manufacturers. And with manufacturers still offering a wide variety of carpets, due to this recommendation by Miraftab et al., (1998), the option of zero-waste manufacturing is included in the model as it is still deemed achievable up to a certain degree.

D.1.3 Zero-emission recycling

Some aspects of carpet tiles are highly recyclable. Nylon is one of these resources that is relatively easily recycled. Just like the zero-emission production means, this means treat the processing of EOL carpets to make resources for new carpets as a (close-to) zero-emission process. This is again achieved by selecting the best performing energy source in terms of emissions, albeit not a pure zero-emission energy source. Different from the production process is that during the recycling process of nylon, by its very nature, emissions are caused. This is because the nylon fibers are separated from the backing material through shredding the carpets. This causes miniscule particles to be released into the air. This alternative assumes that these particles are captured and will not be released. This can be achieved by for instance creating a complete vacuumed shredding system with very fine filtering systems. The energy requirement of this shredding process is added onto the resource costs and creates a trade-off on costs of recycled resources versus virgin resources.

D.1.4 Zero-emission resources

Lastly, zero-emission resources were identified as a means to limit emissions in the production process of carpet. Resources are purchased at the market and are quite easily obtained. However, the mining of these resources is also to be included as a cost to the manufacturing process, although these costs might not belong to the carpet manufacturer (arguably) or even belong to the country in which the carpets are produced. This research decided to allocate these resource gathering costs to the industry incorporating these resources to the final product, being carpet. Some of the resources that go into the carpet are created from finite resources. One of the materials required to create the touch & tones carpet tile is limestone. Limestone is traditionally mined in big quarries using heavy machinery such as dump trucks and excavators, thus having a big impact on the environment. However, limestone can also be recycled from other sources and thereby limiting the environmental impact. This means assumes that all resources used in the carpet are from fully sustainable sources, meaning little to no emissions are produced during the creation or production of these resources. This assumption makes it so that the exact material composition of a carpet tile is of lesser importance: within this scenario the carpet composition might change.

D.2 TRANSPORTATION AND REVERSE LOGISTICS PHASE RESOURCE LEAKS

Like the resource leaks that occur, also the transportation processes involve a reliance on finite resources through the usage of fuel. By several sources, the reverse logistics process has been identified as a key component in order to achieve a circular economy. As such, this second phase was quickly identified to be an area where gains are to be made in terms of sustainability. This section discusses the discovered means that will solve some leaks in the transportation and reverse logistic processes.

D.2.1 Relocation of production facilities

Prior to the generation of policy alternatives, the spatial positioning of the two major carpet production facilities in the Netherlands was mapped. An important insight arose by doing this: the geographical locations of Tarkett/Desso (blue) and Interface (red) is less than optimal. Interface, located in Scherpenzeel, is located near the center of the Netherlands. Tarkett/Desso is located more south. When considering service range, this means Interface is the most efficient choice to supply the most northern part of the Netherlands. This distance is determined to be approximately 176 km beeline. However, drawing a 176 km radius circle around the Scherpenzeel factory, shows this sets the service radius to the whole of the Netherlands.

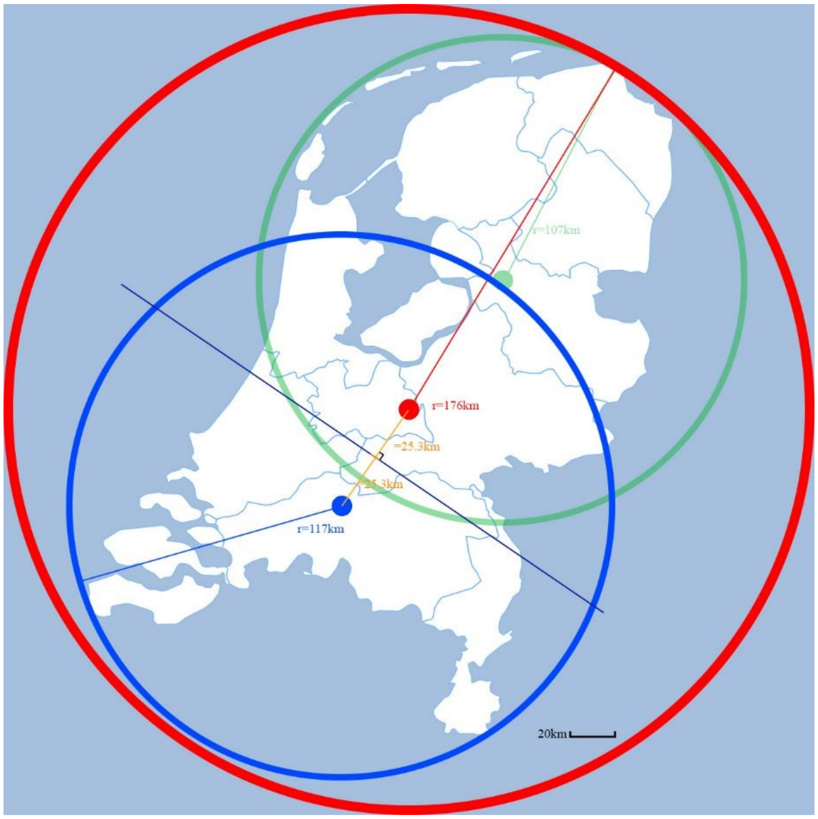


Figure D1. Theoretic service range of Dutch carpet tile manufacturers.

It is then identified what the exact middle is from Tarkett/Desso to Scherpenzeel, and a line is drawn. Anything below this line is closer located to the Tarkett/Desso Waalwijk plant. This resulted in a service radius of 117 km. Depicted above is this analysis. Theoretically speaking, a loss of societal wealth is thus achieved. The optimal setting would be Tarkett/Desso supplying everyone in the lower half of the Netherlands, and Interface supplying the upper half. In order to minimize overlap in service range, this would mean Interface locating more northernly in the Netherlands.

However, as chapter 3.3 identified, there is one more carpet manufacturer in the Netherlands with a high capacity. This was the Condor group, located in Hasselt, north of Interface, indicated as a green marker on the map. Factoring the Condor group into this map results in different key figures. Combining the Condor Group with Tarkett/Desso, the entire Netherlands can be serviced with a maximum radius of 117 km, meaning a truck never has to drive further than 117 km (in a straight line from point to point) to supply a customer with carpets. Supplying a customer in the extreme north as well as the extreme south results in a total single trip distance of 224 km beeline (assuming the customer orders the product closest to their location). Without the Condor Group in this calculation, this same scenario results in a maximum of 176 km beeline kilometers driven, and a total trip distance of 293 km, being 69 km more. As discussed in chapter 3.3, the calculations made in this research will be based on the position of both Interface and Tarkett/Desso. As such, the average distance to supply the customer will be based on the maximum radius (Interface, 176 km), divided by two, resulting in an average service range of 88 km (beeline). This figure does not account for routing and geographical limitations and represents merely a straight distance from factory to customer. In order to compensate this, the model will include a function that will convert beeline to actual kilometers and will accept actual kilometers as well.

In conclusion, this alternative assumes that the shipping distance is limited by relocating a production facility. This alternative assumes that customers pick the supplier closest to them, which will prove to be an unlikely scenario. It does however allow to calculate the effects of optimal spatial planning. The moving of a production facility seems rather big and elaborate, and thus be out of bounds by the set constraints and objectives. However, assuming that permits are taken care of, this relocation of a factory could be taken care of within a year. This includes the construction of the new factory location, as was discovered through inquiries with several industrial building contractors. The financial burden to move an entire operation is significant, however the payoff of relocating could be a very long term payoff and thus possibly might be worth it. If this means is presented as an optimal solution, this cost aspect will be further discussed, and a detailed cost estimate is then highly advised.

D.2.2 Zero-emission transportation

Instead of altering the transportation distance to decrease emissions, one could also try to lower the emissions per kilometer. This is best achieved by changing from combustion engine vehicles to zero-emission vehicles as they are known, such as battery or hydrogen fuel cell powered vehicles. These vehicles are assumed to have lower emissions than the diesel or gasoline powered counterparts. Electric vans and trucks are slowly getting introduced into the market, the same upholds for hydrogen powered trucks. These are estimated to be fully commercially available within the next ten years. Although these vehicles have a lower loading capacity due to their increased weight, their loading capacity is equal to that of the combustion engine vehicles, as the limiting factor for carpet tiles is volume rather than weight. This means calculates the effect of battery/fuel cell vehicles, but again should not be interpreted as a fully zero-emission transportation alternative. First of all, just like the zero-emission production alternatives, the energy used by these vehicles (electricity or hydrogen) has to be generated and transported into the vehicle. During this process, losses occur and just like the energy used by the factory's machinery, it is not fully zero-emission. Furthermore, in vehicular transportation, a degree of emissions will always occur through the emission of particulate matter from tires, brake pads etc. As such, this alternative will not treat transportation to be absolutely zero-emissions, but rather approach zero-emission through obtaining the best-in-class performing energy to power these vehicles. Hydrogen trucks are assumed equal in emissions and usage to electric trucks and thus will not represent a separate category in the model.

D.2.3 Local collection of EOL carpets

As discussed by Oudenbroek, Interface's policy is to bring back EOL carpets to the factory. Here, these carpets are unfortunately not recycled but rather await disposal. So, the manufacturer comes to reclaim their carpets at their end of lifecycle, just to dispose of them themselves. This causes unnecessary distance travelled as every municipality in the Netherlands is required to have their own waste disposal sites. This means assumes that carpets can be delivered to, and be disposed of, in every municipality, thus eliminating the requirement of these EOL carpets to travel back to the manufacturing site. These waste disposal sites then have to be equipped with machinery to process carpet and possibly facilitate the recycling of certain components. To achieve this, every municipal waste deposit site should then be equipped with a carpet shredder and separating machine. Although this means would limit transported distance, it does not solve the problem of ownership. This would be a cheap way for the carpet manufacturer to dispose of their waste, simply by letting their customers take care of it. It would then also not stimulate any effort to produce fully recyclable carpet tiles. As such, if this means proves to be effective, a major policy adaptation is to be created discussing the issues that could arise and generate ways to mitigate this negative effect.

D.3 WASTE DISPOSAL PHASE RESOURCE LEAKS

The final phase in which gains are to be had was identified to be the waste disposal phase. In this phase, uses for the remaining material are evaluated. Currently landfilling is the go-to disposal option, which was identified to be of negative value to society in terms of sustainability. Thus, alternatives are sought to direct these carpets from landfills to other disposal methods where they are either less polluting or have some sort of value left at their end-of-lifecycle. The following means were generated.

D.3.1 Incineration with heat & energy regeneration

Municipal house waste is incinerated at waste disposal plants. Through this incineration, heat is generated, which is harvested and partially converted into electricity. This makes that household waste ends up supplying households with electricity via the grid or of warmth via district heating. Although carpet is not considered household waste by any means, it still has calorific value. Meaning when totally combusted, it does supply some energy which can be harvested. This led to the investigation of supplying waste treatment plants with industrial quantities of EOL carpet for heat and energy regeneration. Incineration of EOL carpets would mean that EOL carpets regain some sustainability compared to landfilling as there is some gain to be had. However, it still permanently disposes of valuable resources and thus will not limit the virgin resource requirement.

D.3.2 Fiber Reinforced Concrete (FRC) downcycling alternative

A downcycling application of EOL carpets was found in Fiber Reinforced Concrete (FRC). This topic is widely researched, and it appears that adding nylon fibers to concrete during the manufacturing process could strengthen the concrete. Up to 2% of the concrete’s mass should be replaced by nylon fibers to achieve maximum strength and strain resistance (Wang, 1999). There is thus an alternative to downcycling nylon fibers from carpets to concrete. There are however quite a few drawbacks to this plan. First and foremost, it does not limit the strain on virgin resources. Rather: if anything, it increases the strain on virgin resources. Not only does it not affect the resource requirement for carpets, the FRC is now contaminated with nylon and cannot be recycled into concrete again (Naqvi et al., 2018). This process requires the separation of backing material from the nylon fibers, which requires specialized equipment. These high value nylon fibers are then used to create an extremely low-value product being concrete. One carpet tile has enough nylon fibers to produce roughly 15 kg of FRC. But with relatively low environmental costs to produce concrete, the primary effect of this means is diverting these carpet tiles from landfills. As this is the most common and suggested fix for diverting EOL carpets from landfills, this option is included in the list of means. It does pose however a severe limitation in the fact that it merely moves the problem of waste disposal: when carpets cannot be landfilled, in the FRC alternative the backing material is landfilled as will the FRC be at its EOL.

D.3.3 Insulation material downcycling alternative

Looking for ways to deal with EOL carpet tiles and/or nylon fibers, through a creative thinking process, the idea arose to turn these fibers into building isolation material. In Sami culture, a lot of pelt and wool is used for its insulating purposes. As such, old logging cabins often have areas insulated with sheep's wool. Although the properties of nylon are vastly different from wool, humans also use layers of (nylon) clothing to stay warm. The key is to trap air between two layers. From this thought, combined with the fact that carpet is known to insulate well, the idea arose to explore the possibilities of creating an insulation material out of nylon fibers. This insulation material would aim to be an alternative to rockwool, which proved to be a highly polluting material to create. This alternative does however assume that only the nylon fibers are used in the creation of this insulation material. Depending on the way this nylon in processed for the insulation purposes, it could be reclaimed afterwards and be reverted back into clean nylon. Instead of moving the problem to another industry, like the FRC alternative, this is more of a temporary storing solution without the nylon losing its value. Furthermore, it does not only save in emissions by eliminating the need for rockwool, it saves on energy consumptions by the household or company as well. This effect is however not modeled.

The exact insulation properties of nylon are however unknown. As such it is also unknown how the nylon fibers can best be treated to form an effective form of insulation. Ideally, these nylon strands would be untreated and be injected into cavity walls so that they do not lose value. It is however likely that these nylon strands will have to be mixed with some sort of adhesive. Depending on the results of the analysis of using nylon as building isolation purposes, this study cannot conclude on the effectiveness of nylon as insulation material. If the model results are positive, a recommendation is made to investigate the insulating properties of nylon and carpet tiles as a whole in greater detail.

D.3.4 Full circularity (closed-loop recycling) alternative

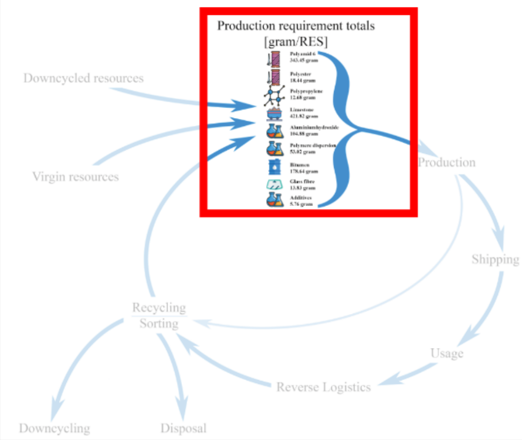
Finally, the fill circularity alternative is presented. This means is highly anticipated by the industry themselves, which see circularity as a great marketing tool to get public support. And by all accounts this is theoretically the best option available. This alternative assumes that every component of a carpet tile can, and will, be recycled and be used to create new carpet tiles with. This is based on findings by the Deutsche Umwelthilfe (2017, February) that state that mostly all material from a carpet tile can be recycled back into raw carpet tile materials. This means would drastically decrease the need for virgin resources. There are however a few limitations to the full circularity means. Unlike the name implies, full circularity could never be achieved. Full circularity assumes that all material is reused to create new material of equal value. Glass is a perfect example of this: a glass jar can be melted and from that same amount of material a new glass jar can be produced. Carpets lose materials as they are in use, even up to

12% in their lifespan according to Miraftab et al. (1998). Meaning that there will always be a deficient of 138 grams of material during the creation of a carpet tile from an EOL carpet tile. This deficit has to be compensated for in order not to have a declining production quantity. Thus, the strain on virgin (finite) resources is limited, not eliminated. Then there is the cost aspect. Nylon is relatively cheaply recycled into pure new nylon. The carpets backing layer however is more difficult to separate and to split into individual resources. This means will then discuss two scenarios: one being that only the nylon fibers are recycled into new carpet (of which the energy requirement is known), and the other scenario is that the entire carpet tile is recycled. For this, the energy requirement to transform the backing material into raw resources is needed as data.

E MODEL INPUT PARAMETERS

With the establishment of the resource steams, this model is ready to be turned into a computational model used to calculate the various effects required in answering the sub questions. This is done through the following process. First, variables are sought that are required as input into the model. These variables are factors concerning the system operation, like the percentage of recycled resources or the transport efficiency. These input factors are presented in appendix F, including a critical reflection. After the input variables are found, the throughput is described. This is a description of the product that follows from these input variables. Then, output data is described. This describes what the model eventually reports to the researcher.

E.1 MODELING INPUT



In order to operate the model, the user has to supply the model with several data points. These data points are considered input and are subject to change: a different production process, different shipping method or different recycle to virgin resource ratio alters the results. An attempt is made to make the input data as simply as possible, to provide the model with a low threshold for further use. Instead of for instance having to supply the model with emission data per carpet tile, it is opted to have that calculated through the input data “means of transport”, “shipping data” and “transport load”.

E.1.1 Production Requirement totals

For production requirement totals, the exact resource requirement is used as input. Carpets are a heterogeneous product, meaning every carpet tile has a different production method and energy requirement. This model was deliberately not designed to incorporate different production methods of carpets, as it was deemed not to take away from the general effects of the identified means to increase the sustainability of the entire carpet production system. As such, it was opted to select one type of carpet tile and use this as the benchmark carpet tile for the remainder of the study. This carpet tile had to be specified per resource, in order to facilitate the adaptation of other types of carpet tiles in future studies.

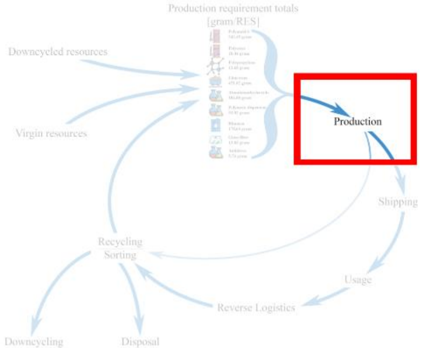
It was opted to select the carpet tile Touch & Tones 103 by Interface as the benchmark carpet tile. This is one of the bestselling carpets by interface and is primarily focused on industrial use, thus sold in larger quantities. Furthermore, documentation on the Touch & Tones 103 carpet tile was made available by Interface, meaning exact material composition could be presented, decreasing the uncertainty of this research. When replicating this study or applying the model to another type of carpet composition, this material requirement is to be altered. The following material (displayed in grams per carpet tile) is required to produce one tile of the set standard (Bossenmayer et al., 2019, January).

Table E1

Resource material listing per carpet tile

Name	[%]	[g/tile]
Polyamide 6	29.8	343.445
Polyester	1.6	18.44
Polypropylene	1.1	12.6775
Limestone	36.6	421.815
Aluminum hydroxide	9.1	104.8775
Polymer dispersion	4.6	53.015
Modified bitumen	15.5	178.6375
Glass fibre	1.2	13.83
Additives	0.5	5.7625
TOTAL	100	1152.5

E.2 PRODUCTION



Other than the material requirement, some other factors are required for the actual production of one carpet tile. These requirements have the ability to either increase or decrease the sustainability of the produced product. The following input data was identified:

E.2.1 Energy requirement & energy source

The production of carpets on large scale happens fully industrially, meaning with big machinery. These machines have an energy requirement which can be presented in gigajoule (GJ). The source of this energy however determines the emissions of these machines, assuming no other emissions (other than heat) are produced. By selecting an energy source, this emission is calculated.

E.2.2 Production waste

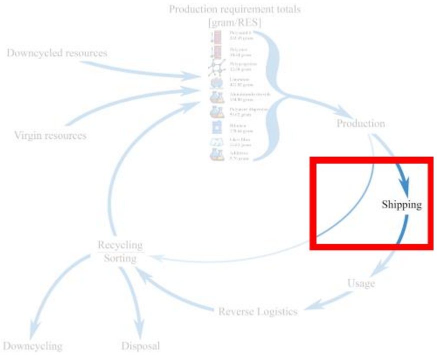
When considering the output of the production method, the production waste dictates how much produced product ends up being shipped to the customer. Misprints, trimmings and other types of productional errors are common to occur during any manufacturing process. This effect is captured in the factor production waste and displays a percentage of product that is produced but does not end up (eventually) at a customer but is directly binned.

E.3 SHIPPING

For the shipping aspect of this logistical chain, some standard traditional shipping aspects are required as input. The expected input is as follows:

E.3.1 Distance to customer & quantity to customer

First and foremost, the distance to the customer is required as input, given in kilometers. Besides distance, also the quantity of carpet tiles is expected as input. This is key in the calculation of the emissions per tile.



E.3.2 Transport means & energy requirement

Next, the transport means is selected. Given the national scale of this research, the transport options exclude air transport and international shipping. Rail and inland waterway transport are included but are not expected to be used within the Netherlands. Transport by foot/bike, or through motor scooter or motorbike is not included as it generally cannot transport any cargo. It must be noted that each transport method has a (limited) carrying capacity, which will be presented in table F.4.3. The following transport means have been identified:

Table E2

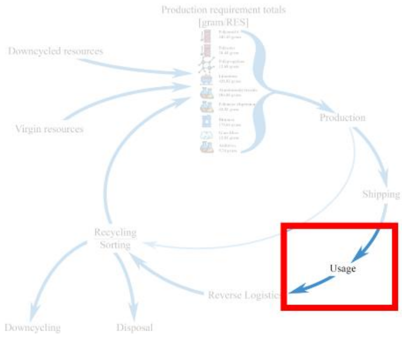
Transportation means overview on capacity and fuel types

Transport means	Capacity	Common fuel types available
Car	Low	Electric, Diesel, Gasoline, LPG
Van / Car + trailer	Low-Med	Electric, Diesel
Truck (box trailer)	Med-High	Electric, Diesel
Truck (Semi trailer)	High	Electric, Diesel
Barge	Very High	Residual fuel oil
Rail	Unlimited	Electric, diesel, combined

These means of transport are however also subject to a specific type of fuel. The fuel types and efficiencies are detailed in Table F7 (Appendix F.4.1). Hybrid means of transport is incorporated by a percentual selection of range per fuel type.

Lastly, the average transport range is calculated in a distance measured without confines to roads and/or geographical data. In other words, the route is a beeline: it is one straight line from origin to destination. Road transport is rarely in one straight line. As such, when non-factual kilometers are used, the average distance is assumed combined with a percentage of beeline to real kilometers. This percentage of the beeline distance is added to the beeline distance to get a simulated real distance travelled across roads. Studies in the United States found this conversion factor to be about 1.4 (Boscoe, Henry & Zdeb, 2012).

E.4 USAGE

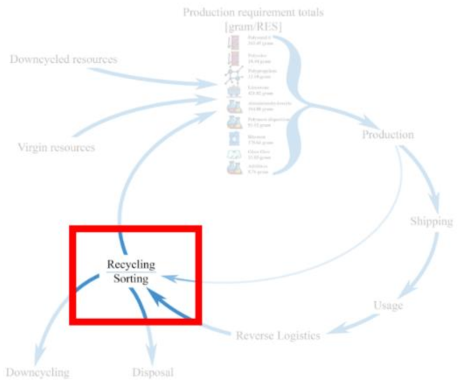


Usage of the carpet describes the lifespan and the energy requirement of the carpet while in use. Within this scope however, the energy requirement while in use is not considered. Although of course several maintenance related activities, such as cleaning the carpet and vacuuming the carpet, require energy, it is deemed that this energy is universal and does not affect the logistic circle of the carpet. As such, usage only requires 2 types of input. The first input is on the lifespan of the carpet: how long does the carpet last in day-to-day use. This is entered in years and has an effect on the discount while calculating the environmental impact. The second factor of usage is the loss of material. It may be possible that some materials are lost through the usage of the carpet. For instance, fibers that become detached from the backing and are lost, through fire/burning or through the process of corroding. This loss will be factored in through a percentage of original material loss but is expected to be marginal at best. This is not to be confused with material that has to be discarded for being too stained, as this will be represented by the recycling and sorting stage.

E.5 REVERSE LOGISTICS

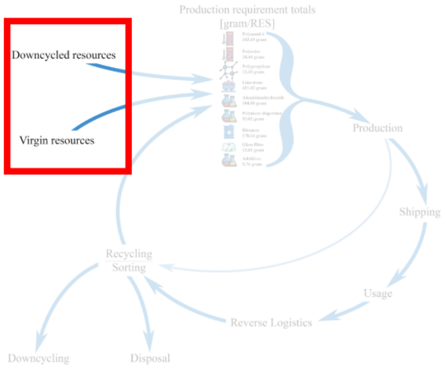
The reverse logistics input is almost identical to the shipping input in factors but might be vastly different from the factual data from the shipping input. The reverse logistic process might include different means of transport or bundling and thus different transport ranges. In order to use this tool to compare policy measures, the model will automatically assume the data to be equal to the shipping phase, but it is advised to revise this data and adjust where necessary.

E.6 RECYCLING/SORTING



The recycling and sorting phase are key in determining which carpets are suitable for recycling, and which are not. There are three possible paths a carpet can be send to from the sorting phase: recycling (used to make new carpets), downcycling (used to make another, less valuable product), and disposal (no recycling value: ending up in landfills or incinerated). The very first input measure is the percentage of resources that go through each individual stream. Note that the unit here is resource, not carpet, as it is possible that for instance the fibers can be recycled, but the bitumen backing cannot. The second required input is the energy requirement of the recycling process. This and the third input, the energy savings through recycling, plus emissions savings/costs make for a total environmental calculation. If for instance the backing of a carpet can be used to strengthen concrete, the separation of fibers and backing causes ‘x’ emissions, yet ‘y’ emissions are saved because less concrete is required in the product. This is also highly dependent on the downcycling (and disposal) method, making the fourth input variable.

E.7 DOWNCYCLED RESOURCES/VIRGIN RESOURCES



In order to achieve circularity as is expressed the main goal of Interface, a closed-loop recycling stream is deemed necessary. This stream is denoted as the α-steam. The resource requirement from downcycled resources and virgin resources is then the total requirement minus the α. As per α, both the downcycled resource stream (β) and the virgin resource stream (γ) require input into the percentage of each resource supplied. For the downcycled resources, the downcycling energy requirement and environmental costs are to be factored into account. This is calculated to calculate the reuse costs minus the landfill costs of this product. For the virgin resources the mining costs (environmental and energy) are to be entered into the model. This makes for an overview of total expected emissions, total emissions saved compared to landfilling/incineration, and energy requirement.

E.8 MODELING OUTPUT

The output of this model is the data required to answer some of this research main questions and is used to fill the knowledge gap. There are data points that have been identified as majorly insightful, although close inspection of the entire model after a run might also serve to gain a better understanding of the entire logistic/value chain. Every process modelled, besides usage, will cause some emission and equals an energy requirement. These will be featured in the output report.

There are two sub-output results displayed. These are aimed at small portions of the entire model. The shipping process, usage and reverse logistics processes combined result in insights in logistic emissions. The sorting/recycling and downcycled resources processes combined result in a recycling efficiency rating. The total model however ultimately results in a count of caused emissions and energy requirement. This calculation is compared to the nil-alternative in order to conclude how it compares to any other option.

F MODELING ASSUMPTIONS & DATA

For the creation of the quantified model a few key figures were used, assumptions were made, and calculations took place in order to deliver a comprehensible model. Within this chapter of the appendix, these modeling decisions will be discussed, and the sources for the key figures will be presented.

F.1 TILE SPECIFIC DATA

The first overview of data are specifics regarding the set unit of carpet tile. Meaning this chapter specifies what exactly entails one unit of carpet tile that is discussed to be the universal standard throughout this study. For this study, the Touch and Tones 103 tile by Interface is selected and used as the standard.

F.1.1 Tile composition

This section discusses the materials required to make one carpet tile of the set unit. The exact composition of this tile is as follows:

Table F1
Resource specification carpet tile

Resource	Grams/tile
Polyamide 6	343.445
Polyester	18.44
Polypropylene	12.6775
Limestone	421.815
Aluminum hydroxide	104.8775
Polymer dispersion	53.015
Modified bitumen	178.6375
Glass fibre	13.83
Additives	5.7625
TOTAL WEIGHT	1152.5

This is entirely based on the Environmental Product Declaration (EPD) as provided by Interface on the Touch & Tones 103 product line (Bossenmayer, Peters & Schindler, 2019). Polyamide 6, better known for its English name Polyamide 6, or simply “nylon 6”, are the face fibers for the carpet itself. This amounts to roughly 30% of the entire carpet’s weight. All other ingredients are then used to attach the nylon fibers to the carpet and to form the dampening backing of the carpet tile. The total weight of the carpet is set at 1152.5 grams, the exact sum of all components. The EPD by Bossenmayer et al. (2019, January) confirm that no resources are lost in the process of carpet production, and all above mentioned resources are combined into one carpet tile without any waste.

F.1.2 Dimensions of the carpet tile

With the weight known, the total dimensions and weight table can be created. The standard measure of one unit of carpet tile in this research is set to be at 50x50 cm. According to the research by Bossenmayer et al. (2019, January), the height of a tile is measured at 1.06 millimeters in total, of which 6 mm fiber. This results in the following measurement table:

Table F2

Measurements and weight of a carpet tile

Length	50 cm
Width	50 cm
Height	1.06 cm
Weight	1152.5 gram

Although packaging will increase all factors: length, width, height and weight, this study assumes a packaging free shipping, meaning no material is required to ship the individual tiles other than fully renewable packaging methods.

F.1.3 Resource costs

Speaking in terms of renewable methods, one of the three inbound flows for the creation of carpets is a virgin resource flow. Bossenmayer et al. (2019, January) concluded that for the creation of one unit of Touch & Tones 103, no recycled materials are used. In other words: all resources are virgin. The costs of virgin resources in this research is most frequently expressed in terms of Gross Energy Requirements (GER), translating it to a general requirement of energy for the mining, processing and preparing of the resources. The eventual emissions are thus dependent on the conversion from energy to greenhouse gasses (GHG), being in this model a selection of electricity provision sources. The following energy is required for each of the resources needed to produce one carpet tile:

Table F3

Emission costs of virgin resources

	MJ/kg	MJ/Tile	kg CO_2-eq./tile	Source MJ	Source CO_2-eq
Polyamide 6	137.6	47.26	3.125	Hammond et al., 2008	CE Delft & RvO, 2018
Polyester	380	7.01	0.063	Hammond et al., 2008	CE Delft & RvO, 2018
Polypropylene	95.4	1.21	0.025	Hammond et al., 2008	CE Delft & RvO, 2018
Limestone	0.85	0.36	0.004	Hammond et al., 2008	CE Delft & RvO, 2018
Aluminum hydroxide	10.5	1.10	0.069	Hammond et al., 2008	CE Delft & RvO, 2018
Polymer dispersion	59.4	3.15	0.175	Hammond et al., 2008	CE Delft & RvO, 2018
Modified bitumen	47	8.40	0.105	Hammond et al., 2008	CE Delft & RvO, 2018
Glass fibre	28	0.39	0.033	Hammond et al., 2008	CE Delft & RvO, 2018
Additives				No data	No data

As mentioned before, the total emissions are then dependent on the selected conversion of mega Joules to CO_2-equivalent emissions. However, for additives, no data was found. Without specification of these additives, no GER can be formed. The EPD reveals that additives make up for 0.5% of the total weight of the carpet tile, equaling little over 5.5 grams. The lack of data and small percentual share in resource requirement make it so that additives are set to zero: the model does not factor any emissions into account for these additives. With emissions of these additives known, it is advised to rerun the model with this information.

F.2 PRODUCING & RESOURCE MANAGEMENT

The process of producing one carpet tile involves heavy machinery and thus also energy. This section discusses the energy requirement deemed to convert the resources into one carpet tile. This includes the machinery in order to form the carpet tile, but also include the GER of the recycling processes. The following processes have been identified:

F.2.1 Production energy requirement

The costs of energy during the production stage is dependent on the material created. Research by Sim & Prabhu (2018) indicate 7 processes for the raw resources to end up as one carpet tile. These seven processes can be grouped together in two groups: the preparation of the top layer face fibers and the attaching of this layer to, and the creation of, the backing layer. The following energy requirement was calculated:

Table F4
Energy requirement production process

Process	MJ/tile	Source
Nylon fiber production	0.58525	Sim & Prabhu, 2018
Backing + completion	1.9155	Sim & Prabhu, 2018

For this calculation, the assumption was made that polyamide 6 in its entirety forms the top layer and is not used elsewhere in the carpet. Following this assumption, the top layer production ends at the tufting process, and the backing production starts with steaming of the product as displayed in chapter 3.2.1 (Figure 3) which is based on the findings by Li (2007).

F.2.2 Closed-loop recycling energy requirement

The closed-loop recycling process includes EOL carpets that are being transformed into new carpets, as well as productional waste that gets recycled into new carpets. The energy requirement of these processes is based on the research by Sim & Prabhu (2018) and is expressed in megajoule per kilogram material.

Table F5

Energy requirement separation process EOL carpet tiles

Process	MJ energy requirement per kg material [MJ/kg]	Source
Separating backing from nylon fiber	0.1652	Sim & Prabhu, 2018
Nylon fiber recycling	0.264	Sim & Prabhu, 2018

The carpet tile first goes through a process of milling and separation: this is intended to separate the nylon fibers from the backing material. Following this process, the nylon fibers are prepared and processed into raw nylon 6 spools, ready to be used in the production of new carpet tiles. This process makes it so that full tiles enter the first stage, and only some of this material gets processed into the second stage. Although the energy requirement of the second stage is higher, given the fact that a full tile weighs 1152.5 grams, of which only 343 grams of nylon are able to be processed in the second stage, the first stage requires the most energy per carpet tile (Li, 2007). Unfortunately, no uses for the discarded backing material have been found and are thus sent to the disposal installation (Sotayo, Green & Turvey, 2015).

F.3 ENERGY COSTS

As discussed earlier, resource costs expressed in Gross Energy Requirements (GER), and display an amount of energy that is required for the mining process. In order to convert this energy into emission data, a conversion factor has to be applied. This conversion is based on energy source emissions. It is worth noting that this is a simplification: in practice the mining of a resource will rarely involve one kind of energy: it requires heat, electrical power, fossil fuels for mobile machinery etc. If data is available that exactly covers the total emissions of all types of energy generation combined, it is strongly advised to use this for the modeling. In order to achieve the best results however, the model can be run with the worst-case-scenario in terms of emission: choosing the least environmentally sustainable energy generation method used in practice, as well as the most sustainable method, will result in a reliable bandwidth within the operations actual emissions should lie.

The type of energy as used by the processing and production plants is primarily electrical energy. The following table lists the types of energy found to be available within the Netherlands and lists the emissions of kilograms CO_2-equivalents per gigajoule produced. This list is generated by researching all available power options within the Netherlands (Harmelink, Bosselaar, Gerdes, Boonekamp, Segers, Pouwelse & Verdonk, 2012). A source for the emissions of renewable/“zero emission” energy sources was found in the respected Intergovernmental Panel on Climate Change (IPCC) by Bruckner et al., (2014), the other data are from governmental used reports and thus are specifically tailored for the Dutch market.

Table F6

Emissions per energy source

Type of energy	Kilogram CO_2-eq. per GJ	Source
Solar	13.3	Bruckner et al., 2014
Wind	3.1	Bruckner et al., 2014
Geothermal	10.6	Bruckner et al., 2014
Hydropower/ocean	6.7	Bruckner et al., 2014
Biomass	109.6	Vreuls & Zijlema, 2009
Petroleum	71.9	Vreuls & Zijlema, 2009
Natural gas	63.1	Vreuls & Zijlema, 2009
Coal	94.0	Vreuls & Zijlema, 2009
Nuclear	3.3	Bruckner et al., 2014

Within this scheme it becomes clear that renewable zero-emission energy sources do in fact have emissions. Depending on the scale of the analyses, one can dispute that the productional emissions of, for instance, a solar panel have to be calculated through into the total emissions when regarding emission per kilowatt. Due to the large quantities of energy required by the industry, it was opted to include this effect into the emission calculations. Another controversial modeling assumption is made in the fact that nuclear energy is modelled to have little emissions, and thus appears to be one of the two best power sources. Of course, nuclear energy is known for its unsustainability as the waste product is highly dangerous to the environment and all beings and cannot be processed. This is however difficult to translate into a CO_2-equivalent emission. Thus, the pure emissions are considered by calculating the creation of the required resources, transportation and storage of the waste product, with an important side note that the option of nuclear energy will has to be modeled to reflect unsustainability within the model. It is however also noteworthy that all energy generation methods have side effects that occur that are not modelled. Windmills and solar panels have a limited lifespan, nuclear waste is a hazardous material, biomass causes above average particulate matter and this list continues on.

F.4 TRANSPORT MODALITY SPECIFICATION

An important factor in determining the sustainability of carpet recycling is the logistics. The (cost) efficiency of returning the carpets to the factory could well determine if the recycling effort reduces or increases the environmental strain. As such, the transporting options are included in the model. This section discusses the available transport options with their limitations and emissions.

F.4.1 Transport alternatives & emissions

The common unit for transport emissions is often presented in tonkilometer, or tkm. This is the unit of emissions for the transport of one ton of weight over 1 km. This emission factor is then determined by the load and the efficiency of the vehicle. Traditionally only diesel engines are used for hauling cargo over longer distances, as it is more fuel-efficient and durable than gasoline (Goen & Ivory, 1978). Although currently suffering limited availability and usage, this model included some newer and more unconventionally transportation means that are expected to gain popularity in the future. These include fully electric powered trucks. For bigger shipments than a singular truck, two other options have been made available for within the Dutch borders. These are barges (inland ships) and rail transport. Although theoretically available, these options will prove to be more useful for international shipping/longer distances as there is a limited reach for these transport means. The following list was composed:

Table F7

Emissions per vehicle per tonkilometer

Type vehicle	Gram CO_2-eq. per tkm.	Source
car, gasoline	344.0	Calculations (F.4.1.1)
car, diesel	328.0	Calculations (F.4.1.1)
car, hybrid	360.0	Calculations (F.4.1.1)
car, LPG	280.0	Calculations (F.4.1.1)
car, electric	187.0-328.0	Wietschel, Kühnbach & Rüdiger, 2019
Van, diesel	630	Stimular, 2011
Van, electric	359.1-630	Wietschel, Kühnbach & Rüdiger, 2019
Truck, 3-10t, diesel	480	Stimular, 2011
Truck, 10-20t, diesel	300	Stimular, 2011
Truck + trailer (max 50t), diesel	95	Stimular, 2011
Truck, 3-10t, electric	273.6-480	Wietschel, Kühnbach & Rüdiger, 2019
Truck, 10-20t, electric	171.0-300	Wietschel, Kühnbach & Rüdiger, 2019
Truck + trailer (max 50t), Electric	54.2-95	Wietschel, Kühnbach & Rüdiger, 2019
Barge (MAX 32TEU)	65	Stimular, 2011
Barge (MAX 96TEU)	75	Stimular, 2011
Barge (MAX 200TEU)	60	Stimular, 2011
Barge (MAX 470TEU)	50	Stimular, 2011
Train, electric	25	Stimular, 2011
Train, diesel	30	Stimular, 2011
Train, combined	27	Stimular, 2011

Although the emissions of vehicles are widely research and thus readily available in tkm units, in two cases this proved to be an issue. The unit conversion of passenger emissions to tkm for cargo for personal vehicles proved to be somewhat difficult and little scientific backing to this was found. As such, based on personal experience and research, a conversion scheme was devised. The second issue regarding lack of data was found in the emissions of electric vans and trucks. For this, a conversion table was created and explained in table F9.

F.4.1.1 *Tonkilometers for personal vehicles (cars)*

A unit for cargo transportation is tkm and is rarely associated with regular (personal) cars. However, relatively small quantities of carpet can still be transported in a regular vehicle. Relatively, as in: a mid-size station wagon has a trunk of 500L, which can be expanded to 1500L by removing the second row of seats. Within this 1500 L, or 1.5 m^3, 1000 carpet tiles could be transported if unlimited by weight restrictions, equaling the square footage of 250 square meters, enough to cover all floors of the average Dutch home twice (Centraal Bureau voor de Statistiek, 2013).

For the creation of tkm from passenger km, an experiment was conducted. Within this experiment, the average fuel consumption of the empty vehicle is compared to the maximum laden fuel consumption. This experiment was conducted by attaching a 1000L water tank to a BMW Type F31 320d, one of the best sold mid-size station wagons (and general cars) in the Netherlands. This car was then driven 10 km, the exact same path and in the same manner, both laden and empty. The board computer was then examined and used to calculate the average fuel consumption for the identical trip. Although not an entirely scientific, the results were that an unladen BMW F31 averages 1/17.4 l/km. The exact same trip with 1000 kg of load averaged out at 1/10.9,which is about two thirds (63%) of the efficiency of the empty vehicle. As such, it was concluded that for this specific vehicle, the conversion from passenger km to tkm would mean adding two thirds in emissions to the vehicle, as two thirds more fuel is needed to travel the exact same distance. Using the Stimular (2011) data to calculate the average emissions of cars per kilometer, these were multiplied by 1.6 to calculate the tkm for a vehicle ($Car_{tkm} = (Car_{emissions} * 1.6)$). Although different types of fueled or engine cars could behave differently under load, the results from this experiment are assumed to be equal across the entire range of vehicles. Differences for emissions per type of fuel were included, and the base data of these emissions are presented in table F8.

Table F8
Conversion table to calculate emissions per tonkilometer

Type vehicle	Gram CO_2/km	Gram CO_2/tkm	Source
car, gasoline	215	344	Stimular, 2011
car, diesel	205	328	Stimular, 2011
car, hybrid	225	360	Stimular, 2011
car, LPG	175	280	Stimular, 2011

F.4.1.2 *Tonkilometers for electric trucks and vans*

Unfortunately, due to the newness of the technology, not a lot of data is available regarding the energy efficiency of electrical trucks A conversion factor was built in accordance with the findings of Den Boer, Aarnink, Kleiner & Pagenkopf (2013, p.114) and CE Delft (Den Boer, Brouwer & Van Essen, 2008) combined with the insights of a report commissioned by a state in Australia (Green Truck Partnership, 2014). This latter study concluded that the energy consumption of electric heavy-duty cargo vehicles is on average just 27% of the energy required by the combustion version of that vehicle. The energy requirements for cars was based on the study by Howey, Martinez-Botas, Cussons & Lytton (2011), and at 0.62 MJ/tkm deviates slightly from the 0.65 MJ/tkm that would be estimated by applying this 27% conversion ratio. For the car, this more scientifically reliable 0.62 MJ/tkm is maintained, for the heavy duty cargo vehicles, the 27% conversion ratio is used, presented in the lighter colored numbers below.

Table F9

Conversion table to calculate energy requirement per tonkilometer

	Diesel [gram CO_2/tkm]	Diesel [MJ/tkm]	Electric [MJ/tkm]
Car	328	*2.42*	0.62
Van	630	*3.5*	0.94
Truck 3-10t	480	*5.9*	1.59
Truck 10-20t	300	8.5	2.30
truck + trailer (<50t)	95	*11.1*	3.00

F.4.2 Emissions electric vehicles

As discussed before, through vehicular motion emissions occur. Only using the CO_2-equivalents of the costs of energy regeneration thus causes an under-estimation of the actual emissions through movement. In order to compensate for this, emissions associated with the mere vehicular movement are also considered. These are the emissions that occur from the moving of the vehicle, mainly in terms of brake pad and tire wear. Studies have found to be the emissions of internal combustion engine driven vehicles, excluding the tailpipe gases, is equal to the emission of electric vehicles (Timmers & Achten, 2016). In other words: a traditional vehicle and an electric vehicle cause particulate matter in an equal ratio regarding the movement. There are thus different claims regarding the profitability of electric vehicles over combustion vehicles. Some researchers claim that electric vehicles have the potential to have a maximum potential to lower emissions by 43% compared to diesel vehicles (Wietschel, Kühnbach & Rüdiger, 2019), while others claim that the emission is virtually equal (Buchal, Karl & Sinn, 2019).

As this study is not primarily focused on identifying transportation emissions, it was opted not to select one of these as the truth. It is a highly controversial topic that hosts for a lot of different emission claims. Consequently, these numbers will be presented in scenarios: from “best case”, being a 43% reduction, to worst case, being 0% reduction of greenhouse gas emissions by electric vehicles. As such, it will also be included in the model as an input parameter.

F.4.3 Transport capacity

Every vehicle has a loading capacity, and this loading capacity determines the number of trips required to complete a shipment. As discussed in appendix F.4.3.2, a car has a loading capacity of 500 L, 0.5 m^3, and it has a maximum weight as well. This research also provides an overview of the maximum loading capacity of the selected vehicle, but it does not match a shipment to the optimal transport means automatically. It is thus of importance that the researcher checks the compatibility: a car cannot ship 40 tons of cargo in one trip, whereas it makes no sense to transport 400 kg of carpet tiles with a barge. The following transport means and their respective transport capacity and volume are as follows:

Table F10

Overview of transportation limitations and quantities

Type vehicle	Transp. capacity in metric ton	Transp. capacity in m^3	Max carpets (limited by)	Source
Car	1	0.5	188-566 (space)	BMW, 2020
Van	1.5	11.7	1301 (weight)	Mainfreight, 2020
Truck, 3-10t	8	48	6941 (Weight)	Mainfreight, 2020
Truck, 10-20t	16.14	96.1	14004 (Weight)	Mainfreight, 2020
Truck + trailer (max 50t)	32.15	100.3	27895 (Weight)	Mainfreight, 2020
Barge (MAX 32TEU)	768	1056	398490 (space)	Bellmore, 2008
Barge (MAX 96TEU)	2304	3168	1195472 (space)	Bellmore, 2008
Barge (MAX 200TEU)	4800	6600	2490566 (space)	Bellmore, 2008
Barge (MAX 470TEU)	11280	15510	5888160 (space)	Bellmore, 2008
Train (MAX 94TEU)	2256	3102	1177632 (space)	Janic, 2008

In the following paragraphs, this data, and the assumptions on which they are based, are more elaborately discussed. The following calculations are based on the following facts: one carpet tile of Touch & Tones weighs exactly 1152.5 grams, measures 50 cm in width, 50 cm in length and 1.06 cm in height, equaling a volume of 2650 cm^3.

F.4.3.1 *Assumption regarding the capacity of alternative fuel vehicles & volumes*

For the calculation of the maximum cargo capacity, no distinction has been made in regard to the fuel type. It is thus assumed that a diesel car can transport an equal amount of cargo to the gasoline version of that car. This same assumption upholds for electric and fuel-cell vehicles, but this might be disputable due to the higher weight of the vehicle itself (Berjoza & Jurgena, 2017). Realistically, heavier electric vehicles can transport less cargo, as Dutch regulations forbids vehicles to exceed a maximum admissible weight. However, with a lack of data reporting on the estimated weight of electric vans and trucks, the maximum loading weight of an electric vehicle and combustion vehicle are assumed to be equal.

Furthermore, this study excludes any margin for shipping material such as packaging and pallets. It is assumed that carpet tiles can be stacked individually on top of each other if needed to be, and thus eliminating the need for packaging material. In practice however it is more than likely that carpet tiles will be boxed in sets and shipped on pallets. This effect can be modelled by adjusting the volume of the carpet tile, incorporating the average packing dimensions per tile, but is considered out of scope for this research.

F.4.3.2 *Car*

As discussed in appendix F.4.3.2, the maximum loading capacity of a car was determined to be 1.5 m^3, the standard capacity being 0.5 m^3. The maximum loading weight, based on the maximum allowable mass of a BMW F31, was determined to be 1 ton (BMW, 2020). Following these figures, a personal car, assuming the 500L storage, can transport a maximum of 188 carpet tiles. Increasing this loading capacity by folding the second row of seats down, the limiting factor remains space, allowing a maximum of 566 tiles to be transported. The loading capacity of 500 liters will however be considered the standard, as not all vehicles offer the ability to either fold down the second seating row or are smaller than a mid-size station wagon.

F.4.3.3 *Van*

The loading capacity of a van was based of the data provided by a shipping company. This van was determined to have a maximum load of 1.5 ton, and a capacity of 11,7 being significantly higher. Thus, making weight its primary limitation, making it capable of hauling 1301 carpet tiles at the maximum.

F.4.3.4 *Trucks*

For trucks, the maximum load is considered the limiting factor across the board. The smallest truck, those able to transport 3-10 tons, have a loading capacity of 48 m^3, allowing maximum transport of 32000 carpet tiles. This equals close to 37 tons in transport weight. As such, the amount of carpets that are to be transported are calculated using the weight restrictions. For the smallest truck available, this equals nearly 7000 carpet tiles at transport. Mid-size trucks offer a capacity of little over 14.000 carpet tiles, and the trailer offering storage and transportation of close to 28.000 tiles.

Again, it is worth noting that this is based on the weights and maximum loading weight of combustion trucks. Any fuel cell or fully electric truck with a higher eigen weight might be restricted to a lower cargo weight.

F.4.3.5 *Barge*

Barges operate mainly with shipping containers, often referred to as Twenty foot Equivalent Unit, or TEU. These TEU's have a maximum loading capacity of 24 tons each and are estimated to have an efficient loading volume of 33 m^3 (Bellmore, 2008). This makes for a limitation in weight of 20.824 carpet tiles, and a limitation in volume of 22.000 tiles. Thus, each TEU can ship a maximum of 20.824 carpet tiles.

F.4.3.6 *Train*

Trains can also be equipped to transport TEUs. Passenger train lengths are often limited to platform lengths, as passengers have to get on or off. A cargo train is less limited by this factor. Within Europe the train is limited by its length at 620 meters, allowing for 94 TEU units. With a low emission this makes the train look like a very preferable means of transport. However, the same upholds for the barge, the loading sites are limited, and often require further transport to the destination. It is very unlikely that the final destination of the carpet is located in a port or at the rail cargo station. This extra transport factor is not included in the model, as it was deemed unlikely that either barge or train will be used in the given scope, that is limited to the Netherlands. With one truck being able to transport close to 7000 m^2 of carpet tiles, both barge and train are expected to only be used for export reasons.

F.5 DISPOSAL & DOWNCYCLE OPTIONS

Not all material will be recycled into new carpets. Some carpets will be used in different industries where the material is of lesser value (downcycled) or will be disposed. This section discusses the emissions and required energy of these processes.

F.5.1 Waste disposal options & emissions

When waste cannot be reused or recycled, it is either stored or disposed. The current two options for waste disposal in the Netherlands have been identified to be either landfilling or through incineration. Through incineration heat and energy can be reclaimed, thus limiting the emissions of incineration with a fraction of the saved heat and energy generation costs. The even more unsustainable option is to landfill: simply storing the waste in a dumpsite, possibly exposed to the elements, and leaving it there until it perishes. The emissions of landfills are calculated with a scenario of methane reclamation: landfills produce methane which can be captured and reused. The following emissions per kilogram waste, not specific to carpets, have been identified:

Table F11

Disposal emissions

Disposal option	kg CO_2-eq./kg waste	Source
Landfill	0.75	Arena et al., 2003; Manfredi et al., 2009
Incineration	0.643	Helftewes et al., 2012

Through the reclamation of heat and energy generation, the incineration option for general waste is clearly the better alternative. However, these figures are generated based on averages in the waste processing plants. Running merely carpet tiles might result in vastly different emission results. However, without any known figures on emissions of carpet tile waste processing, these averages will be used as they are the best available data.

F.5.2 Recycling/downcycling options & emissions

Besides the closed loop recycling costs, as discussed in appendix E.6 there are also emissions and costs attached to the downcycling of carpets for another industry. Currently, the only use identified for EOL carpets is in the concrete industry (Wang, 1999). Here, carpets are incorporated in the concrete to form fiber reinforced concrete, FRC in short. By replacing 0.5% to 2% of the volume of concrete by (nylon) fibers, concrete shows increased strength and durability (Wang, 1999). However, not all carpet waste is suitable for this purpose. As the name suggests, FRC requires only the nylon fibers, which are assumed to be fully recyclable as discussed in chapter D.3.2. The backing material for carpets, which are the biggest problem, also have no use in FRC. It is then the question why an option to downcycle should be explored when the product can be recycled with little additional effort. However, some carpets are simply deemed too stained, or the top layer too worn out to be recycled. Then this option might be a viable alternative to divert carpets from landfilling or incineration, limiting the strain on virgin resources. This option is explored through the creation of an emission count of this downcycling process.

The creation of concrete from virgin resources was discovered to be 0.15 kg CO_2-eq. per kilogram concrete produced (Liu, Ahn, An & Lee, 2013), which is not to be confused cement with a much higher environmental impact. Of this kilogram, a maximum of two percent, or 20 grams, of concrete can be replaced with downcycled nylon fibers. To calculate the effect of downcycling carpets to FRC, the costs of a 20 grams savings in concrete is compared to the costs of 20 grams of downcycled nylon fiber. For this, the costs of separation and transport to the sorting facility is calculated per gram of downcycled nylon. This however gives just a one sided view, and the equation should not stop there. By downcycling, material is also diverted from the landfill. The effect of this also has to be calculated in the total effect of downcycling.

Again, an unlimited demand for nylon fibers to create FRC is assumed in this calculation and model.

F.5.3 Nylon supply

Like the downcycling of the top layer to the concrete industry, Interface is known to downcycle material by the fishing industry (Lampikoski, 2012; Khoo, 2018). Interface downcycles fully nylon EOL fishing nets into nylon yarn for carpets. The costs of this process are equal to the extrusion costs of nylon, and are set at 0.264 MJ/kg (Appendix K.1.4). It is however disputed that this downcycling of fishing nets yields any positive effects for the environment, as these fishing nets require to be shipped more than 18,000 km. If local fishing nets could be used, the downcycling could yield greater results and a higher increase in sustainability. However, this effect is likely offset by major shipping distances from importing EOL fishing nets from halfway across the world.

G SYSTEM DIAGRAM CORRELATIONS

The following table is made to increase the legibility of the model. This table consists of a central factor representing any of the circles within the system demarcation. It shows which factors affect this central factor and which factors this factor affects. The bold factors are the main output factors, as presented by the ovals on the right side of the system diagram. Green color reflects means, red color represents external factors. The symbols reflect a positive or inversed correlation. It is advised to refer to this table when examining the full system diagram

Table G1

System diagram correlation overview

Affected by	Central factor	Affects
ZE-Manufacturing (-)	Energy emission	Production costs (+)
ZE-Recycling (-)	Energy emission	
Production energy requirement (+)	Energy emission	
Energy Emission (+)	Production costs	**System emissions/energy req (+)**
Recycling (-)	Production costs	
Production quantity (+)	Production costs	
ZE-manufacturing (-)	Production costs	
ZW-manufacturing (-)	Production costs	
ZE-resources (-)	Production costs	
Circularity (-)	Production costs	
Resource costs (+)	Production costs	
ZW-manufacturing (-)	Production quantity	Production costs (+)
Order quantity (+)	Production quantity	*Shipping (+)*
	Production quantity	*RL (+)*
Production quantity (+)	*Shipping*	**System emissions/energy req (+)**
Factory relocation (-)	*Shipping*	
ZE-transport (-)	*Shipping*	
Transportation distance (+)	*Shipping*	
Transportation modality costs (+)	*Shipping*	
Production quantity (+)	*RL*	**System emissions/energy req (+)**
Factory relocation (-)	*RL*	*Disposal (+)*
Local collection (-)	*RL*	*Recycling (+)*
ZE-transport (-)	*RL*	*Downcycling (+)*
Transportation modality costs (+)	*RL*	
Transportation distance (+)	*RL*	
Carpet wear (-)	*RL*	
RL (+)	*Downcycling*	**Virgin resource reliance (+)**
Insulation (+)	*Downcycling*	**System emissions/energy req (-)**
FRC (+)	*Downcycling*	**Amount of disposed waste (-)**
RL (+)	*Disposal*	**Virgin resource reliance (+)**
Incineration (+)	*Disposal*	**Amount of disposed waste (+)**
	Disposal	**System emissions/energy req (+)**
RL (+)	*Recycling*	**System emissions/energy req (-)**
Circularity (+)	*Recycling*	**Amount of disposed waste (-)**
	Recycling	**Virgin resource reliance (-)**
	Recycling	Production cost (-)

H MODEL RESULTS & INTERPRETATION

As with any model, it is a representation of the view of the researcher. As such, it has assumptions and modeling decisions that alter the results. It is of great importance to have some degree of certainty as to how reliable the model is. This reliability is tested through the model validation. Ways are sought to test how the model behaves, and if this behavior is logical, non-extreme, and in line of the expectations. There are several ways to conduct a model validation. This appendix discusses the following methods of validation: extreme tests, result validation and expert validation. These are all meaningless if a thorough understanding of the operations of the model are not established. As such, this chapter discusses the nil-alternative and the interpretation of the results prior to validity testing.

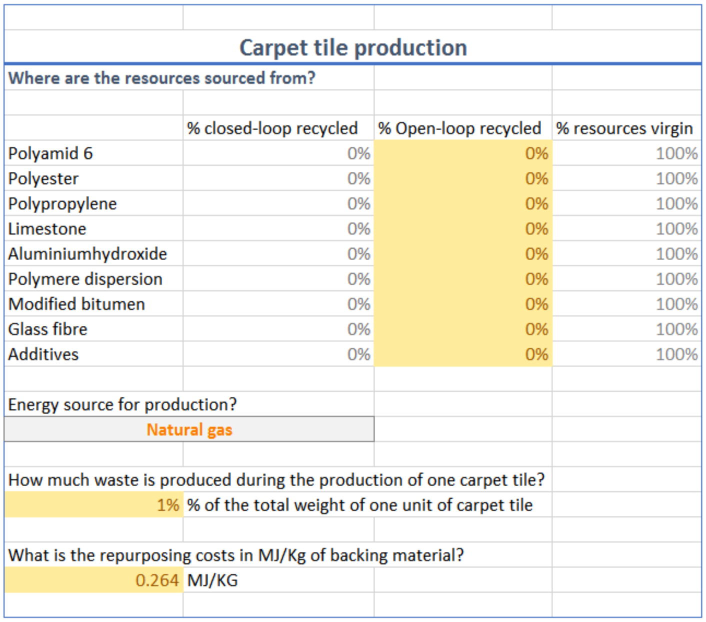
H.1 NIL-ALTERNATIVE DESCRIPTION & RESULTS

The created model is used as a tool to measure the effectiveness of different sustainability increasing measures. In order to conclude on the effect of such measures, the newly created scenario is to be compared to the current established scenario. This is the nil-alternative, also called benchmark alternative, and reflects the current situation. The results of this benchmark alternative are the outcome of several decisions by the researcher, which do not necessarily accurately reflect the real situation. This is why validity tests are conducted in order to conclude how well the world was modeled.

As the benchmark alternative, insight is to be created on which data this benchmark was established. The following decisions were made in the establishment of this nil-alternative:

H.1.1 Carpet tile production data

The first data on which the nil-alternative is established is in regard to the carpet tile production data. Within this nil-alternative the production of a carpet tile is said to be purely constructed out of virgin resources. This assumption is based on the EPD of the carpet tile set standard throughout this study. The material specification also originates from this EPD and is based on the Touch & Tones 103 carpet tile by interface. The energy source for the production is set to natural gas, the most



Carpet tile production

Where are the resources sourced from?

	% closed-loop recycled	% Open-loop recycled	% resources virgin
Polyamid 6	0%	0%	100%
Polyester	0%	0%	100%
Polypropylene	0%	0%	100%
Limestone	0%	0%	100%
Aluminiumhydroxide	0%	0%	100%
Polymere dispersion	0%	0%	100%
Modified bitumen	0%	0%	100%
Glass fibre	0%	0%	100%
Additives	0%	0%	100%

Energy source for production?

Natural gas

How much waste is produced during the production of one carpet tile?

1% % of the total weight of one unit of carpet tile

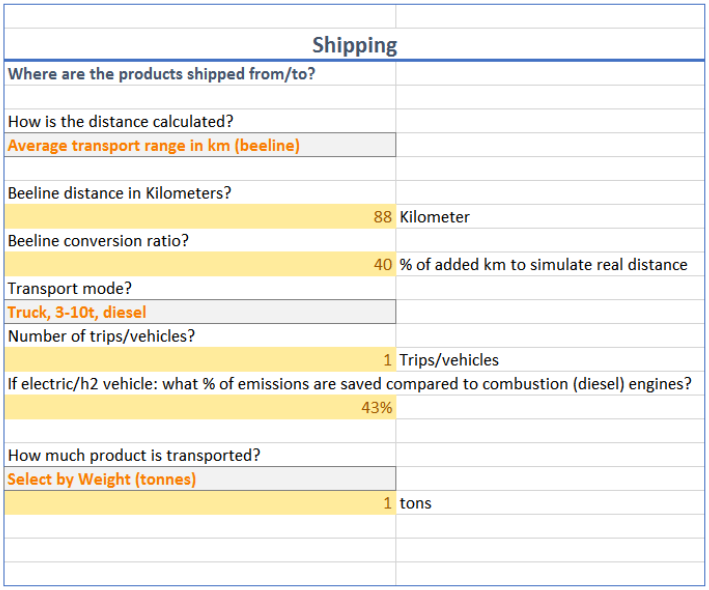
What is the repurposing costs in MJ/Kg of backing material?

0.264 MJ/KG

commonly used energy source within the Netherlands. Natural gas is midrange energy source in terms of greenhouse gas emissions: not emitting terribly much GHGs, also not one of the best performing energy sources. The nil-alternative further assumes that for every carpet tile produced, one percent of that carpet tiles weight is trimmed off and considered excess. Since there is no recycling, the energy requirement for repurposing backing material is unused.

H.1.2 Shipping data

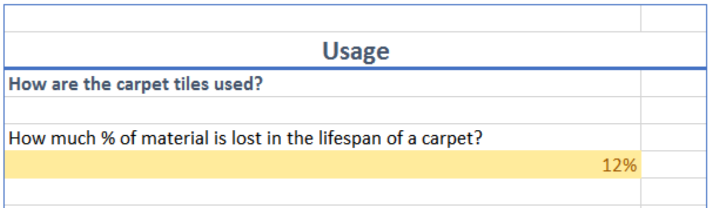
Based on the current location of the two primary carpet manufacturers, the service range of these manufacturers is determined to be 88 kilometers, as the system is bounded to Dutch country borders. This is a distance in a straight line, which in practice rarely occurs. Thus, a 40% beeline to actual kilometer conversion is applied. Operating within Dutch national borders, 50 ton trucks are deemed excessive. Thus, it is opted to choose 3-10 diesel ton trucks for transport, which will complete the full shipment in one trip. Finally, the product quantity is set to 1 ton, equaling 867 tiles or 216 m^2 of flooring area.



Shipping	
Where are the products shipped from/to?	
How is the distance calculated?	
Average transport range in km (beeline)	
Beeline distance in Kilometers?	
88	Kilometer
Beeline conversion ratio?	
40	% of added km to simulate real distance
Transport mode?	
Truck, 3-10t, diesel	
Number of trips/vehicles?	
1	Trips/vehicles
If electric/h2 vehicle: what % of emissions are saved compared to combustion (diesel) engines?	
43%	
How much product is transported?	
Select by Weight (tonnes)	
1	tons

H.1.3 Usage data

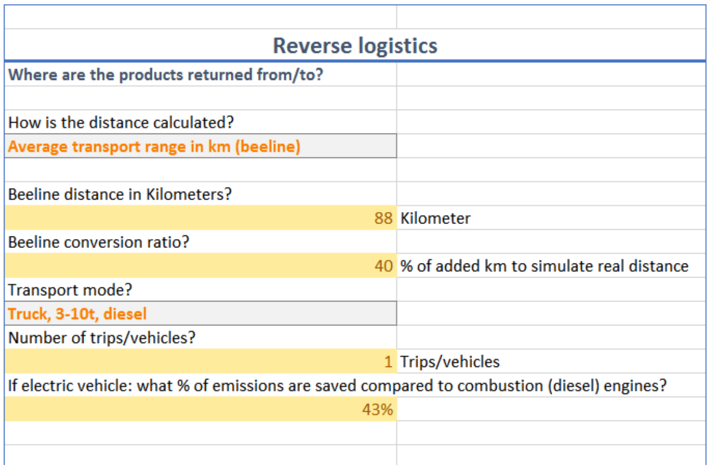
The manufacturers EPD specifies that through regular usage, 12% of the products material is lost at the end-of-lifecycle. This number of material loss is copied into the model.



Usage	
How are the carpet tiles used?	
How much % of material is lost in the lifespan of a carpet?	
12%	

H.1.4 Reverse logistics data

The data in the reverse logistics section of the model are largely equal to that of the transportation section. The model expects the carpet manufacturer to recollect the carpets at the same location as drop-off. The same modality is used (3-10 ton truck) which completes the shipment in one trip.



Reverse logistics

Where are the products returned from/to?

How is the distance calculated?

Average transport range in km (beeline)

Beeline distance in Kilometers?

88 Kilometer

Beeline conversion ratio?

40 % of added km to simulate real distance

Transport mode?

Truck, 3-10t, diesel

Number of trips/vehicles?

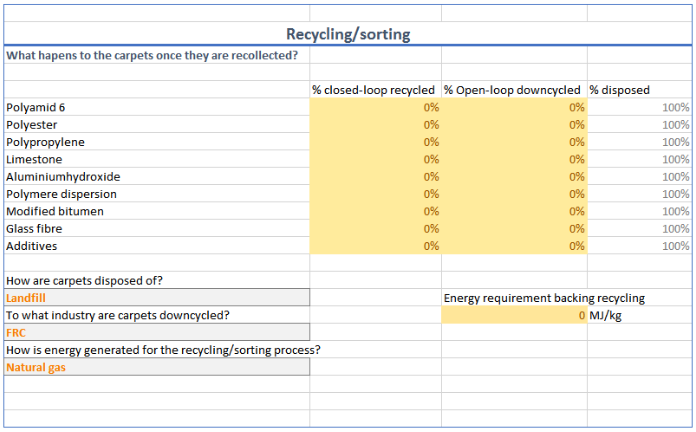
1 Trips/vehicles

If electric vehicle: what % of emissions are saved compared to combustion (diesel) engines?

43%

H.1.5 Recycling/sorting data

Perhaps the most complicated input section of the model. The nil-alternative assumes that no resources are repurposed and that the entire carpet tile ends up at the landfill without any processing or separation of resources. Thus, the percentage of disposed material is 100% across all resources. Carpets are disposed through landfilling. No carpets are recycled/downcycled, thus no energy (source) for recycling/downcycling is required.



Recycling/sorting

What hapens to the carpets once they are recollected?

	% closed-loop recycled	% Open-loop downcycled	% disposed
Polyamid 6	0%	0%	100%
Polyester	0%	0%	100%
Polypropylene	0%	0%	100%
Limestone	0%	0%	100%
Aluminiumhydroxide	0%	0%	100%
Polymere dispersion	0%	0%	100%
Modified bitumen	0%	0%	100%
Glass fibre	0%	0%	100%
Additives	0%	0%	100%

How are carpets disposed of?

Landfill

Energy requirement backing recycling

To what industry are carpets downcycled?

0 MJ/kg

FRC

How is energy generated for the recycling/sorting process?

Natural gas

H.1.6 Nil-alternative results

These modeling decisions as described above result in the following results. These results are considered the benchmark and will be used to calculate the effectiveness of different sustainability increasing measures with. The next chapter will discuss how these results are to be interpreted and read.

Table H1

Emissions and energy requirement nil-alternative

Emissions [kg CO$_2$-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.7	TOTAL	4.9
Virgin	3.6	RL	0.1	Nylon sep.	0.0		
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.0	TOTAL	78.0
Virgin	72.1	RL	1.1	Backing sep.	0.0		
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	20
Manufacturing	11	RL	4	Disposal	0		

H.2 INTERPRETATION OF THE RESULTS

The model puts forth two styles of report pages. The first style is in clear, explanatory matter, best fit for the user of the model. The second style is how it is most frequently presented here, in a table form. With many parameters, results might feel cluttered if not presented correctly or merely descriptively. In order to provide an unambiguous overview of the parameters in this scenario, a structured reporting style is selected. The following table is used to present a quick overview of a scenario:

Table H2

Overview of scenario representation

Production RSS		**Production**		**Transport**		**Lifecycle**		**Reverse Logistic**		**Sorting**	
Closed-loop	x	PWR SRC	x	Distance	x	Loss of Material	x	Distance	x	Recycled	x
Open-loop	x	Waste	x	MODE	x			MODE	x	Downcycled	x
Virgin	x	Tot. Weight	x	# trips	x			# trips	x	Disposed	x

				Emissions EV	x			Emissions EV	x	Disp. method	x
										Downcycle method	x
										PWR SRC	x

This overview corresponds with the steps as described in appendix F. The first column describes the distribution of recycled materials through closed-loop recycling, open-loop acquired recycled/downcycled, represented in percentages of one full carpet tile. The second column indicates the power source (PWR SRC), waste that is inherent to the production (presented in a percentage of weight of a full carpet tile) and the total weight of the batch in ton. The transportation column gives an overview of the total transportation distance (including beeline to actual km conversion), the transport mode, the number of trips and, in the case of an electric vehicle, the CO_2-eq. emission savings of this vehicle compared to the diesel counterpart (Emissions EV). This ranges from 0% to 43% as discovered by Wietschel, Kühnbach & Rüdiger (2019). The lifecycle stage only results in a percentage of loss of material through usage, whereas the reverse logistics process is identical to the transport process in explanation. In the sorting stage, the distribution of EOL carpets to recycling/downcycling/disposal is presented, again using the percentages to indicate the proportion of resources of one carpet tile per channel. This final column includes the disposal method of EOL product (Disp. Method) as well as the downcycle method of EOL product. Finally, a PWR SRC indicates where the power originates from that is required to recycle/downcycle.

The results are also displayed in table form. The following results are displayed:

Table H3

Modeling result tables

Emissions [KG CO2-equivalent]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total		Transp.		Disposal		TOTAL	
Virgin		RL		Nylon sep.		Change	
Closed				Backing sep.			
Open				Effect			
Manufacturing							

Energy requirement [MJ]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total		Transp.		Nylon reclaim		TOTAL	

Virgin		RL		Backing sep.		Change	
Closed				GER disposed			
Open				Effect			
Manufacturing							

Emissions [milligram PM10 per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop		Transp.		Separating		TOTAL	
Manufacturing		RL		Disposal		Change	

H.2.1 Production - emissions

The first table presents the emissions in GWP of the system. The first columns state the emissions that occur during the production process of the carpet tile. The first indicator, RSS tot, gives a complete overview of all emissions by the resources themselves. This is a summation of the following three costs: the emissions of virgin resource gathering, emissions of closed-loop recycling and the emissions of open-loop acquiring and recycling of resources. The energy post discusses the emissions that occur during the production process through the usage of electricity and coloring of the nylon fibers.

H.2.2 Shipping - emissions

The second column, the shipping section, discusses the transportation costs in terms of GWP. This column presents both the transportation and reverse logistics flow (RL) costs in terms of kg CO_2-eq. per carpet tile. In the benchmark scenario, and also when adapting the model to specific needs, many times the reverse logistics costs, getting the product back from the same customer and returning it to the factory, is lower than the initial transport towards to customer. This is due to the fact that carpets degrade and thus lose weight. Through the modeling of this weight loss, the transportation unit of tonkilometer decreases too, resulting in a slightly lower emission of RL product.

H.2.3 Repurposing – emissions

The costs of repurposing are presented in four different factors. The disposal costs are the mere costs of getting rid of all left-over unwanted material. This either proceeds through landfilling or incineration. One way to limit this cost is through recycling/downcycling. All downcycling means identified require only the nylon fibers. Thus, if downcycling is selected, a cost arises in terms of separating nylon from the backing material (“Nylon sep.). The full circularity, closed-loop recycling, alternative however also assumes that the backing material is split to separate each individual resource. This cost is indicated by “backing sep.”. Downcycling yields gains that go beyond the savings in disposal. Materials in other industries are produced with lower emissions through the reusing of EOL (already "paid for") emissions. Thus, these energy savings are deducted from the total emission caused by the carpet production/supply chain. This savings is presented as the effect of downcycling and is presented as a negative number.

H.2.4 Total – emission

The column total shows the total emissions in kg CO_2-eq. per carpet tile as calculated by the model. The change percentage describes how much this deviates from the nil-alternative.

H.2.5 Production – Energy requirement

The first column displays the energy requirement of production. The virgin resource costs display the gross energy requirement of the virgin material and its share. The closed and open loop recycled resources display the energy requirement of repurposing raw (recycled) resources into usable resources for the carpet production. The "energy cost" post indicates how many megajoules are required to operate the carpet producing machines (just the fabrication of the carpet, not the preparation of resources) and the dyeing of the carpet.

H.2.6 Shipping - Energy requirement

The energy requirement of the shipping column is presented by selecting both the transportation mean and weight of reverse logistic product. Each vehicle has a specific energy requirement for transportation, which can be supplied through a diverse amount of energy sources (Diesel, batteries etc.). It translates to the effort of moving cargo.

H.2.7 Repurposing – Energy requirement

The repurposing column of the results display the energy requirements and energy savings of the possible recycling/downcycling process. The first post displays how much energy is required to separate the nylon from the backing layer. "Backing sep." indicates the energy requirement to separate the backing material into individual resources. Depending on the scenario, some material will still end up being disposed. The "GER disposed" cost indicates how much gross energy requirement is disposed in terms of virgin resources. The "effect" shows how much energy is saved through downcycling and/or through heat and electricity regeneration by incineration.

Note that the TOTAL in energy requirement does not add up due to the post of GER disposed. The disposed GER are not part of the energy requirement and serve a mere indication of the losses through disposal. This stresses comprehension of complete data: in itself the downcycling option says little about actual emissions as it is unclear compared to what other alternative emissions are saved. Through running the full model twice, only then the total emission of a scenario can be compared to a nil-alternative.

H.2.8 Total – Energy requirement

The column total shows the total energy requirement in MJ per carpet tile as calculated by the model. The change percentage describes how much this deviates from the nil-alternative.

H.2.9 Production – Emissions (particulate matter)

This column displays the emissions of particulate matter emitted during the open-loop acquiring of the resources, as well as the manufacturing emissions per carpet tile.

H.2.10 Shipping – Emissions (particulate matter)

These columns display the emission of PM_{10} per carpet tile emitted through either the transportation or reverse logistics process. This is merely the result of the emissions by the vehicle.

H.2.11 Repurposing – Emissions (particulate matter)

This column will display if the repurposing of a carpet tile entails the emissions of particulate matter. In the separation of the top and backing layer, particulate matter can be caused, which will be represented here. Also, through waste incineration, some particulate matter is caused. If incineration methods are selected, this cell will display the specific emissions of this incineration process.

H.2.12 Total – Emissions (particulate matter)

This column displays the total emissions of particulate matter in milligram per carpet tile, and a change compared to the nil-alternative.

I MORPHOLOGICAL CHARTS

During this study, different alternatives have been found that possibly pose a solution to the aim of increasing the sustainability of a carpet tile. These solutions represent a wide solution-space with possible overlaps and hidden compatibilities. In order to simply represent the complex and large design space, morphological charts were invented in order to combine separate solutions to form one integrated, all-encompassing, design solutions (Smith, 2007). The design space was divided into three areas where resource leaks were discovered. These areas are the production stage, the transportation stage, and the waste stage. For each of these streams, different alternatives are presented to fix the individual resource leaks. Though the usage of a morphological chart, these individual alternatives are combined into one solution. Any combination of solutions might not always be plausible or realistic (Smith, 2007). Thus, a selection is made of solutions that are likely to exist together or do not conflict. The following table represents the design space, in which all alternatives are listed.

Table I1
Morphological chart

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

Following this table, the following solutions were selected. These encompassing solutions are then described in detail and a simulation is ran in order to calculate the effect of this newly created solution. In the creation of the solution space, a minimum of one option per parameter is to be selected.

I.1 DESIGN SPACE 1: OPTIMAL WASTE DISPOSAL PLAN

Table I2

Design 1, adaptation of morphological chart

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

In the first design space, an option is presented that will pose optimal waste treatment and prevention measures. In this alternative, it is assumed that any manufacturing waste is prevented. EOL carpets are then assumed to be locally collected in every municipality. Here, the nylon fibers are separated from the backing material, and are used for insulation purposes. The remaining backing material is incinerated and assumed to regenerate electricity by doing so. This scenario gives the following results:

Table I3

Design 1, modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.6	TOTAL	3.5
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-28.8%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	-1.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	71.3	Transp.	1.3	Nylon reclaim	0.2	TOTAL	56.9
Virgin	71.3	RL	0.1	Backing sep.	0.0	Change	-27.1%
Closed	0.0			GER disposed	21.2		
Open	0.0			Effect	-19.5		
Manufacturing	3.4						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	1	TOTAL	22
Manufacturing	10	RL	0	Disposal	6	Change	14%

I.2 DESIGN SPACE 2: OPTIMAL CIRCULARITY PLAN

Table I4

Design 2, adaptation of morphological chart

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

The second design space is focused on the concept of circular economy. It aims to produce products as sustainably as possible and eliminate the need for virgin resources. Due to the 12% material loss through the lifecycle, there remains a need for open-loop acquired resources. This scenario assumes that these resources are gathered form open-loop downcycling rather than virgin resources. It also assumes that both the manufacturing process, as well as the recycling process as the transportation will exceed through zero-emission means, meaning a fully renewable energy source of Wind and 43% savings of electric trucks compared to diesel . The following results can be achieved following these assumptions:

Table I5

Design 2, modeling results

Emissions [KG CO2-equivalent]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	0.4	Transp.	0.1	Disposal	0.000	TOTAL	0.5
Virgin	0.4	RL	0.0	Nylon sep.	0.001	Change	-89.7%
Closed	0.0			Backing sep.	0.001		
Open	0.0			Effect	0.000		
Manufacturing	0.0						

Energy requirement [MJ]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	8.2	Transp.	0.4	Nylon reclaim	0.2	TOTAL	12.5
Virgin	7.9	RL	0.1	Backing sep.	0.2	Change	-84.0%
Closed	0.3			GER disposed	0.0		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [gram PM10 per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	4	Separating	0	TOTAL	5
Manufacturing	0	RL	0	Disposal	0	Change	-75.5%

I.3 DESIGN SPACE 3: SHORT TIMESPAN PLAN

Table I6

Design 3, adaptation of morphological chart

	OPTION 1	**OPTION 2**	**OPTION 3**	**OPTION 4**
PRODUCTION	[✓ ZE-manufacturing]	[✓ ZW-manufacturing]	[✓ ZE-recycling]	ZE-resources
TRANSPORTATION	Relocation	[✓ ZE-transport]	Local collection	
WASTE	Incineration	[✓ FRC]	Insulation	Full circularity

The third design space is created with the time constraint in mind. This combination of options is composed to be quickly implementable within the current system. Thus, it focusses on zero-emission energy sources as the main source of sustainability. This design space assumes zero-emission energy sources for the manufacturing and separation of EOL tiles, assumes zero-emission transportation through electric trucks and assumes that at the end-of-lifecycle, the nylon fibers will be reused in the creation of fiber reinforced concrete. This alternative does not eliminate the waste of the bitumen filled backing material of the carpet. With these options selected, the following results are achieved:

Table I7
Design 3, modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	4.3
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-11.4%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	0.4	Nylon reclaim	0.2	TOTAL	76.1
Virgin	72.1	RL	0.3	Backing sep.	0.0	Change	-2.4%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-0.2		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	4	Separating	0	TOTAL	8
Manufacturing	0	RL	4	Disposal	0	Change	-58%

I.4 DESIGN SPACE 4: ALTERNATIVE RECYCLING PLAN

Table I8
Design 4, adaptation of morphological chart

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

The alternative recycling method focusses on the option to recycle EOL carpets into insulation material for construction works. In this scenario, only the production source is set to zero-emission, as it is deemed more time consuming to have all collection sites connected to zero-emission energy sources. The effects of the decreased transportation method combined with the newly found use for nylon fibers results in the following emissions and energy requirements:

Table I9
Design 4, modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	3.4
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-31.0%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	-1.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	71.8
Virgin	72.1	RL	0.1	Backing sep.	0.0	Change	-7.9%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-5.3		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	5
Manufacturing	0	RL	0	Disposal	0	Change	-73%

I.5 DESIGN SPACE 5: ZERO-COSTS PRODUCTION PLAN

Table I10

Design 5, adaptation of morphological chart

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	ZE-manufacturing	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	Local collection	
WASTE	Incineration	FRC	Insulation	Full circularity

Different to full circularity, this scenario assumes that all resource mining methods can be improved to almost achieve zero environmental strain in terms of emissions. However, the carpet tiles at the end-of-lifecycle are deemed impossible to recycle. Thus, this design space favors the decentralized collection of carpets and incineration of the full carpet, including the nylon top fiber, resulting in the following modeling results:

Table I11

Design 5, modeling results

Emissions [KG CO2-equivalent]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	0.0	Transp.	0.1	Disposal	0.7	TOTAL	0.8
Virgin	0.0	RL	0.0	Nylon sep.	0.0	Change	-83.4%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

Energy requirement [MJ]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	71.3	Transp.	1.3	Nylon reclaim	0.0	TOTAL	55.9
Virgin	0.0	RL	0.1	Backing sep.	0.0	Change	-28.3%
Closed	0.0			GER disposed	62.8		
Open	0.0			Effect	-20.3		
Manufacturing	3.4						

Emissions [gram PM10 per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	14
Manufacturing	0	RL	0	Disposal	9	Change	-28.1%

I.6 DESIGN SPACE 6: BUDGET PLAN

Table I12

Design 6, adaptation of morphological chart

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
PRODUCTION	[✓ ZE-manufacturing]	ZW-manufacturing	ZE-recycling	ZE-resources
TRANSPORTATION	Relocation	ZE-transport	[✓ Local collection]	
WASTE	Incineration	[✓ FRC]	Insulation	Full circularity

Finally, a design space is presented in which budget is a decisive factor. In this scenario, the collection of carpets by the industry is halted, thus reverting carpets to local waste treatment plants. For recycling, the least expensive method is selected by opting for fiber reinforced concrete. In terms of production, the installing of PV-cells ensures a zero-emission manufacturing process. This plan results in the following effects:

Table I13

Design 6, modeling results

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	4.3
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-12.1%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]			
Production	**Shipping**	**Repurposing**	**TOTAL**

RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	76.9
Virgin	72.1	RL	0.1	Backing sep.	0.0	Change	-1.4%
Closed	0.0			GER disposed	21.3		
Open	0.0			Effect	-0.2		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	5
Manufacturing	0	RL	0	Disposal	0	Change	-73%

J MEANS - EFFECTS

J.1 TRANSPORTATION LEAKS

The first resource leak that was observed through the creation of the model and through the literature study was found to be in the transportation. With an inefficient (or non-existent) reverse logistics policy, experts agree that a lot of energy is wasted (Cline et al, 2015). This section is aimed to identify means to improve the sustainability of the carpet tile chain by reducing the transportation costs.

J.1.1 Relocation Interface and Tarkett/Desso fix

As observed in figure 4 in chapter 3.3.2, the location of the two major production facilities of carpet tiles in the Netherlands is a determining factor in the service range. Moving the Interface production facility upwards would cause the average service range to decrease, meaning less distance is required to transport goods to a customer. In this scenario, an option is explored to move both the Interface and the Tarkett/Desso plant to the optimal locations. The following two locations were selected:

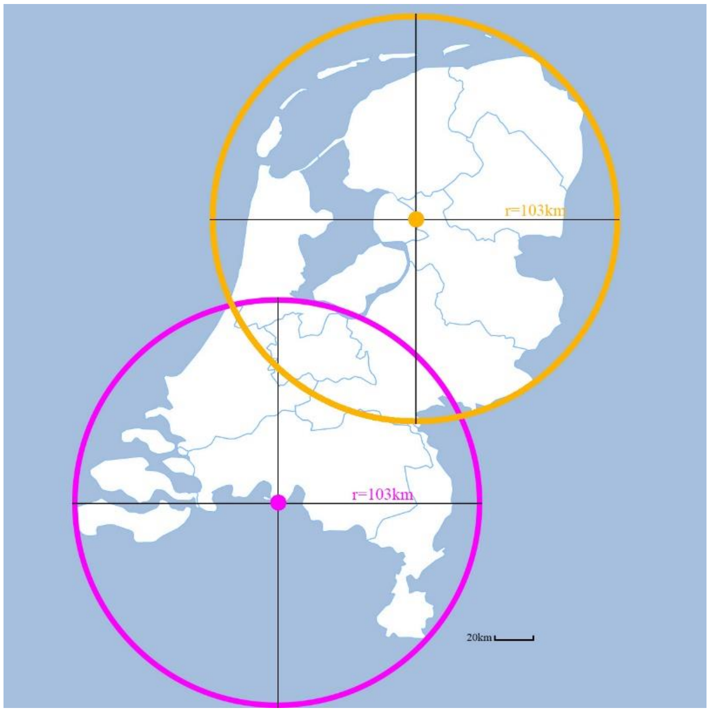


Figure J1. Optimal service range through relocation of factories.

The purple center is located close to the Belgian border and approximated to be close to the city of Baarle-Nassau. The orange center is located to the west of Steenwijk. Note that the distribution of service ranges in this example are in conflict with the demarcation: almost half of the most southern (purple) service range is in Belgium. Through the assumptions of this model that the Dutch border is respected as a system boundary, this would mean a significant smaller market for the purple supplier. This aside, the service range is decreased from a maximum of 176 km in the nil-alternative to a maximum of 103 km, equaling an average transport range of just 51.5 km instead of the original 88 km.

What

Relocate the two primary production facilities from Waalwijk and Scherpenzeel to Baarle-Nassau and Steenwijk to decrease the average transportation distance by 41.5%.

How

Build new production facilities in the above mentioned locations and set the service range to 103 km.

Profit

Relocating two production facilities is an expensive operation. It requires the building of a factory or the adaptation of existing structure(s), as well as require downtime in production due to the necessity to move all material. Purely monetary wise, such expenses have to justify an average transportation decrease of 36.5 km single trip. The costs per km for heavy duty cargo trucks ranges from €1.56 to €2.07 per km according to Panteia (2018), meaning a monetary savings can be achieved ranging from €113.88 to €151.11 per supply trip. A very, very rough estimate of relocating costs include the construction of a new production facility (rule of fist: anywhere between €100,- and €180,- per m^2, Desso in Waalwijk currently has a production facility of over 12.500 m^2) at €1,750,000.-, transportation costs of €50,000.- including the transportation of wide and heavy equipment including the required permits, and another €200,000.- for other various expenses such as maintenance, groundskeeping and infrastructure creation. At two million euros costs for relocation, based purely on transportation gains on a lifespan of thirty years, the breakeven point lies around 500 yearly transportation movements for 30 years.

This is a very rough estimate and serves nothing but the establishment of a vague idea of a return on investment. Before actual policy is considered for relocating, a well thought-out and properly researched cost-estimate is advised, including the additional costs or gains for increased/decreased distances for resource suppliers, risk analyses and uncertainty.

Planet

A similar calculation can be made for the environmental impact of such a relocation. The exact emissions of building a factory is an entire research by itself. The gains are then also highly dependent on the type of building constructed and what it is a replacement for. When an outdated production facility with a low energy score is replaced by a state-of-the-art climate neutral produced facility with better energy ratings, this relocation is easier justified. Then it is also the question of lifespan: how long the company will last in this location. There is too much uncertainty and unknown factors for this research to go into depth on the exact effects of relocation, but in long term it may pay out, as long as certain conditions are met in terms of construction and usage.

Duration

The construction of a new facility is a lengthy process. Although a warehouse is more easily constructed and requires less detail in the finishing than a residential house, the planning and construction stage can easily take up to two years. However, during this time, the operations can continue as usual. The primary time constraint is the downtime required to move the entire operation from one location to another. This is estimated to last anywhere from one to two months, assuming that some machines are thoroughly serviced and upgraded during this move.

Effect

The effect of relocating an entire production facility is of enormous scale. It is a costly operation with a highly uncertain payoff over a very long time. The energy and emissions saved by decreasing the transportation distance to customers eventually has to compensate the emissions caused and energy required by the move.

Table J1
Effects of production site relocation

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.8	TOTAL	4.8
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-2.2%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	0.8	Nylon reclaim	0.0	TOTAL	77.0
Virgin	72.1	RL	0.7	Backing sep.	0.0	Change	-1.3%
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	3	Separating	0	TOTAL	16
Manufacturing	11	RL	2	Disposal	0	Change	-19.1%

As observed, the emissions of shipping are decreased from 0.14 kg CO_2-equivalents per carpet tile to 0.08 kg CO_2-equivalents per carpet tile, a decrease of 41% for the shipping costs post. A 19% reduction is observed in the production of PM_{10} through shipping and in the energy requirement, which is reduced from 1.67 MJ to 0.764 MJ per carpet tile. In regard to the total emissions and energy requirements, this option saves between 1.3% and 2.2% per carpet tile.

Uncertainty

With this operation comes high uncertain. The costs of relocating are always an uncertain factor in even the most public tendering contracts, with numerous buildings exceeding building costs by huge factors (like the Sidney Opera House or more locally, the Betuwelijn, Station Arnhem Centraal or the Noord-Zuidlijn). More so, technological advances in transportation could decrease the costs of transportation in the same timeframe it takes to recover from the extra emissions/energy caused by the move.

Conclusion

Theoretically, relocating the production facilities makes a lot of sense. A big portion of transporting costs can be saved by strategically positioning the two major production facilities within the Netherlands. The costs of such an operation are substantial and the direct payoff for such an operation is marginal (2.8-3.1%). It is furthermore merely a utopian thought to think that a producer will only supply customers in his service range in a free market. Taking the high uncertainty into account, the high costs and the lengthy process of payoff, it is concluded that this method might increase sustainability eventually, but there are more easy ways to achieve the same results.

J.1.2 Alternative fuel transportation fix

As discovered in chapter 3.4.2, the transportation of carpets is an area where resource leaks occur. In chapter 5, the transportation strain is attempted to be minimized by limiting the distance of transport. Another option is to make this transport more efficient/sustainable. This can possibly be achieved through the usage of zero-emission vehicles. This possible solution will explore the costs and gains of using electric and hydrogen transportation means.

Hydrogen vehicles deserve a separate explanation within this model, as it is topic of high controversy. The majority of hydrogen is currently being generated through the usage of fossil fuels (Midilli, Ay, Dincer & Rosen, 2005). Some even claim that an industrial scale hydrogen system cannot be established without the usage of fossil fuels, and that it will never achieve sustainability (Bossel, 2006; Offer, Howey, Contestabile, Clague & Brandon, 2010). On the other hand, other researchers claim that hydrogen has a high potential to be generated fully sustainable, climate-neutral even (Hosseini & Wahid, 2016). This research assumes that by the time that hydrogen vehicles are fully and commercially available, that the hydrogen generation processes have also been improved significantly. This makes for the modeling assumption that any hydrogen generated for the usage in transport, a climate-neutral fully renewable generation process is established, and thus emits close to zero GHG. Furthermore, hydrogen trucks are assumed to have a fuel-cell setup instead of a combustion engine. This fuel-cell converts the hydrogen to electric energy which is then used by the electro-motors. Deviations in weight might make for a slightly different energy to km ratio for hydrogen and battery powered trucks, but as the motors are universal, the same joule to km conversion is used for both the battery powered and fuel-cell powered vehicles.

What

Replace current transportation vehicles with zero-emission vehicles such as hydrogen or fully electric vehicles.

How

Purchase new vehicles, lease or contract through tendering procedures.

Profit

The costs of alternative fuel heavy duty cargo vehicles are currently higher than the equivalent of that vehicle with a combustion engine. A hydrogen fuel cell truck is at €320.000,- purchase price about three times as expensive as a regular EURO-6 truck (Mercedes-Benz Trucks STER, oral inquiry, 2017; Nikola Motor Company, 2017). Electric trucks are a little cheaper than the hydrogen fuel-cell trucks but will costs about twice as much as a regular truck (Zhou, Roorda, MacLean & Luc, 2017). The average life expectancy of a truck is 7.4 years and 13.4 years for truck and trailer combinations (Centraal Bureau voor de Statistiek, 2015, October 19). For the truck and trailer combination, this requires then an additional investment of roughly €16.500,- per year for the hydrogen truck and €7500,- for the battery driven truck. This comes at the assumption that the average lifespan of these alternative fuel vehicles is equal to their combustion counterparts. The average Dutch truck drives an annual 57.450 km per year (Centraal Bureau voor de Statistiek, 2018, November 5). The increased purchasing costs for a hydrogen truck are thus €0.286 per km higher than that of the combustion truck, and €0.130 for the electric powered truck.

At the time of writing the global fuel market is severely impacted by the Corona crisis. Historic data thus is assumed to provide a more durable fuel price. In 2019, the average Diesel price was determined to be €1.356 per liter (Centraal Bureau voor de Statistiek, 2020, August 6), which will last 2 km in a truck. The cost of energy for car charging was determined by the ANWB (2020) to be around €0.60 per kWh, equaling €0.167 per MJ. The costs of hydrogen at a fuel pump was exactly €10,- per kilogram in 2019 (ANWB, 2019, September 27), averaging out at €0.05 per MJ. These electric based trucks (battery and hydrogen fuel-cell) are estimated to use 3 MJ/km. Merely considering the costs of fuel and purchasing price, the break-even point for hydrogen trucks is at 342.000 km, and for the electric truck at 565.000 km, achieved within respectively 6.0 to 9.8 years of usage. This method is thus financially viable based on these criteria. Other criteria are still uncertain as the technology is not widely accessible yet.

Planet

Electric and hydrogen vehicles are considered zero-emission modes of transport. Theoretically, both electricity and hydrogen can be generated fully sustainably and zero-emission. As with all energy requirements, the origin of energy is an important factor of emissions. A major downside of these electric vehicles is their reliance on rare earth metals required for the batteries, electric motors and fuel-cell applications. The absence of batteries makes the hydrogen truck achieve a higher sustainability rating in terms of depletion of rare resources.

Duration

There are currently only a handful hydrogen refueling stations within the Netherlands, and hydrogen trucks are very slowly becoming available to the public with multiple truck manufacturers already taking orders. The Nikola Trucking Company expects to start production of hydrogen trucks in 2023 (Nikola Motor Company, 2018, November). Besides the Nikola truck, Toyota is currently in a trial stage with hydrogen trucks in the port of Los Angeles (Toyota, 2017, April) and DAF has successfully converted some garbage disposal trucks to hydrogen in Eindhoven (Transport-online, 2014, December). Thus, it is estimated that hydrogen trucks will be widely available within 10 years (by the year 2030), backed by the findings of Staffell, Scamman, Velazquez Abad, Balcombe, Dodds, Ekins, Shah & Ward (2019). As for battery pack fueled trucks, commonly accessible companies like Mercedes and DAF have adopted battery operated trucks into their common inventory of trucks and are thus readily available. A few months of delivery time is to be incorporated into the duration as standard with any vehicle manufacturing operation.

Effect

The following results were generated for the zero-emission transport options.

Table J2

Effects of electric transportation means

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.8	TOTAL	4.8
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-2.3%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	0.3	Nylon reclaim	0.0	TOTAL	76.2
Virgin	72.1	RL	0.3	Backing sep.	0.0	Change	-2.3%
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	4	Separating	0	TOTAL	19
Manufacturing	11	RL	4	Disposal	9	Change	-4.6%

The effect of limiting fossil fuel vehicles heavily impacts the emissions of shipping, more so than relocating to an optimal location to limit shipping distances. The emissions decrease by 2.3% while the energy requirement decreases 2.3% as well. This is primarily caused by the notion that electro-motor powered heavy duty vehicles require only 27% of energy that is required by a combustion engine for 1 km of movement (Green Truck Partnership, 2014) and by selecting the highest possible emissions savings possible for electric trucks (43% reduction of GHGs compared to diesel trucks). When an environmentally straining production of hydrogen/electricity is selected, for instance through generation of hydrogen through coal plants, a decrease in sustainability can be observed. These above stated results assume a 43% reduction in GHGs by electric vehicles, but it was argued this factor ranges anywhere between 0% and 43%. 0% obviously being identical to the nil-alternative, the emission factor scales accordingly to this factor (and thus also the total emission savings). As combustion only accounts for 10%

of a vehicle’s PM production, a 10% decrease of PM_{10} is observed for the transportation aspect (Timmers & Achten, 2016).

Uncertainty

Zero-emission cargo vehicles are still a niche market and not a lot of data is available on their functioning. Furthermore, any zero-emission vehicle is only as good as the energy it receives. Meaning that, as discussed in appendix J.1.2., as long as electricity or hydrogen is not produced fully sustainable, the zero-emission vehicle will not achieve its full potential in being an environmentally friendly alternative. However, calculation also shows that this effect might be smaller than the gain of a significantly decreased energy requirement. More uncertainty can be found in fluctuations of price: as technology advances, estimates are that hydrogen trucks (and electric vehicles in general) will become better and cheaper to operate in time (Lee, Elgowainy, Kotz, Vijayagopal & Marcinkoski, 2018). Operating costs of the zero-emission alternatives are the last source of uncertainty: it is mere speculation how the electric truck compares to the diesel truck in terms of durability and service requirement.

Conclusion

There are gains in the adaptation of zero-emission transportation in terms of emissions and energy requirements. It is even financially viable to invest in hydrogen or battery powered trucks. The exact effect of adaptation of zero-emission vehicles is dependent on the method of energy generation, however calculations show that energy choice cannot make the zero-emission vehicle more environmentally straining than the combustion counterpart. This does however assume that the hydrogen (and electric) truck is as good as a combustion truck in terms of lifespan, km per year and maintenance. Deviations in these factors could alter the profitability both in favor of, and against, the adaptation of zero-emission vehicles. In all, it is highly likely that zero-emission vehicles will aid in increasing sustainability throughout the supply chain, with hydrogen vehicles being the better option (quicker return on investment, lower operating costs etc.).

J.1.3 Decentralized collection & repurposing fix

Until now, this study assumed that every unit of carpet tile is returned to the factory. These factories end up disposing the carpets they previously returned to the factory as there is no processing power (Chapter 3.6.1). This is far from efficient. As discussed in appendix D.3, only the nylon fibers of EOL carpets have value in terms of recycling, the backing materials are always disposed of. In this proposition to fix the transportation leak, the effects of decentralized collection of EOL carpets is modeled. In this scenario, the carpets are not required to be shipped back to the manufacturer, but rather to local processing plants and/or “milieustraten”. As the nylon fibers make up for just 33% of the weight of a carpet tile, by bundling, total transport requirements can be cut down by 67%. It does however first require the EOL carpets to be supplied to one of these centralized collection points, which are assumed to have the ability to separate the backing from the nylon fibers.

Within the Netherlands, every municipality is obliged to provide a waste-deposit site. This makes for 355 waste deposit sites across the Netherlands. With a square footage of 33.883 km^2 of land (Central Intelligence Agency, 2020), this makes for an average of one municipality per 101 km^2, or the average size of 10 km length and width per municipality. This makes the average transporting distance to a waste processing plant 10 km (beeline) as well, a steep reduction from the previously assumed 88 km. In case of an established recycling system, additional transportation is required to transport the nylon fibers back to the factory. The decrease in volume and weight can be modeled by adjusting the 88 km distance originally designed to model the return logistics. Through the separation of fibers from backing, only 33% of weight and even less volume remains of a full tile remains. It thus requires only a third of the transportation capacity. For every three trucks that used to collect EOL tiles, only one truck suffices to collect the nylon fibers. Thus, the trips of big shipments in the model can be decreased by 67%. In the case of just one shipment, the effect of bundling and collecting can be modeled by decreasing the transport distance by 67%, simulating that 3 tiles worth of Nylon can be transported at the same costs of one full tile. This results in a reverse logistic distance of $RL_{Decentralized} = \left(10 + \frac{88}{3}\right) * Beeline\ conversion$, making for an average beeline distance of 39.3 km. This is less than half the transportation distance of the current situation.

What

Instead of returning EOL carpets to the manufacturer, collect them at garbage disposal plants which are already commonly available throughout the Netherlands. Here, carpets are directly disposed of, or are processed in order to separate the valuable nylon fibers from the backing material.

How

Supply every waste processing plant with a shredder and separation device. Allow storage of nylon fibers in for instance a shipping container.

Profit

The decrease in shipping distance makes for a cost gain for the carpet owners. The purchasing of the shredder and separation device for the garbage disposal plants could be a costly operation, but the Dutch government already has plans in play to finance the purchasing of these machines in order to stimulate circularity (de Baedts, 2012, may; Ministerie van Infrastructuur en Milieu, 2019, July; Hamer, Braakman, Both & Kwant, 2020). For the final disposal of the carpets, cost ownership is of the essence. Through current operations, by collecting the carpets themselves, the carpet producers become responsible for the waste product. When disposing these carpets, the manufacturer has to pay the garbage disposal facility for the disposal of these carpets (G. Sterk, personal communication, august 14, 2020). By making all “milieustraten” capable of handling carpets, not the carpet producer but the municipality becomes owner of the waste product, thus carrying the costs of the final disposal. This can be averted through numerous constructions like a deposit on new carpets, a crediting system based on the origin of the carpet, or by having manufacturers pay for the collected Nylon 6 fibers upon collection.

Planet

The decrease of shipping distance effectively lowers emissions of GHG as well as decrease the energy requirement. Local collection of waste has the added benefit of better distributing carpet waste across the country, allowing for higher processing capacity.

Duration

Supplying all milieustraten with recycling equipment would put require the ordering of over 300 shredding and air-separation machinery. The size of these machines is then one factor that comes into play determining the speed of construction. If the unit is only to process carpet tiles, the size can be smaller than when it also has to process regular carpets. Seeing the high investment costs, this second option is preferred. No fabricators were willing to set a price or give a time estimation on construction. It is roughly estimated that the construction of one shredder with a big enough workforce and an order of 350 pieces will take on average 10 working days, including waiting on shipments to arrive and delivery. However, with a guarantee of the arrival of such machines, the collection (stockpiling) of carpet tiles could start immediately.

Effect

Only considering the effect of local garbage disposal, not incorporating the recycling of carpets, the following results are achieved.

Table J3

Effects of decentralized EOL carpet collection

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.8	TOTAL	4.8
Virgin	3.6	RL	0.0	Nylon sep.	0.0	Change	-2.2%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.0	TOTAL	77.0
Virgin	72.1	RL	0.1	Backing sep.	0.0	Change	-1.3%
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	16
Manufacturing	11	RL	0	Disposal	0	Change	-19.1%

There is a significant decrease in the reverse logistic costs observed, as expected. Decreasing the range for disposal from 88 km to 10 km beeline makes for a total decrease of emissions by 2.2%, a decrease of energy requirement of 1.3% per carpet tile, and a PM_{10} decrease of 19.1% making this the option score marginally better than the first option of relocating the production plant. This is due to the fact that this alternative reduces the total shipping distance by 218.4 km compared to the reduced 204.4 km by the first alternative.

Uncertainty

There is relatively low uncertainty regarding this option. It calculates the impact of reduced reverse logistic distances through the usage of combustion engines. As observed in the second modeling run, the effect of having zero-emission vehicles has a bigger effect on emissions but requires more energy. The total effect is thus dependent on the implementation of zero-emission vehicles in regard to GHG emissions, but in sight of energy requirement this resource leak fix is of low uncertainty.

Conclusion

Any form of carpet collection through municipalities is an improvement over current policy. As such, if carpets can be disposed of directly at municipal level instead of collection at the factory followed by disposal, a huge transportation cost can be avoided. This however requires an investment by municipalities to process carpets when an attempt is made to facilitate recycling. The government already claimed to cover the costs of these recycling machines. Although it does not affect the shipping distance, the reduction in reverse logistics costs is relatively easily achieved. It does however require strong definition of ownership of EOL product. By collecting EOL carpets, the manufacturer is currently responsible for the disposal (and thus has to pay for disposal). When disposal happens on a municipal level this ownership shifts from the manufacturer to the user. There is no official regulation regarding ownership of EOL carpet waste, and manufacturers collecting the EOL product is merely out of free will. When the consumer has to carry these costs, a fear arises of illegal dumping or the preference of less-sustainable yet cheaper methods of disposal. As such, policy should be formed to ensure the correct collection of EOL carpets. This can be achieved through a deposit-setting, like plastic bottles, or through other contractual arrangements with carpet manufacturers.

J.2 WASTE TREATMENT LEAKS

Another major leak seems to occur in the disposal of EOL carpet tiles. In the nil-alternative, 21.35 megajoules of gross energy requirements per carpet tile is disposed of in a highly environmentally straining manner. This includes high value resources such as nylon and aluminum that are being disposed due to the inability to recycle these resources. This section discusses methods to limit or mitigate these effects. The following fixes to resource leaks in the waste process are identified:

J.2.1 Incineration with energy regeneration fix

Municipal waste is often incinerated at waste incineration plants. These plants offer, besides filtering of emissions, the added advantage of heat and energy regeneration through incineration. For carpets, this option is however not available. This is largely due to the material composition of carpets which is unfit for the incineration plants (G. Sterk, personal communication, august 14, 2020). This results in a loss of 68.87 MJ worth of materials (GER) through landfilling without any recovery. If carpets were to be incinerated, the energy they could supply is depicted in the calorific value. For carpets, the incineration plant TWENCE assumes an average calorific value of 20 MJ per kilogram material but however adds that their current plant is unable to process carpet tiles (M. De Jong, personal communication, august 18, 2020). Through incineration of a carpet tile, 23.05 MJ energy can thus be regenerated potentially, if it would be fit for incineration. This calculation assumes that carpets are fit for incineration without changing the composition.

What

Regain energy by reverting carpet tiles from landfills to waste incineration plants.

How

Through incineration of waste energy is regenerated. For this, alteration of either incineration plants or of the composition of carpet tiles is required.

Profit

Disposal of any quantity of material will come at a financial cost for industries as confirmed by Mr. Sterk (G. Sterk, personal communication, august 14, 2020). Incineration plants thus will not compensate industries for supplying them with fuel for incineration. As carpet tiles are not suitable for incineration, no cost indication of disposal could be provided. Average cost prices of incineration per ton of material based on a 2005 research were found to be €100,- per ton of waste, compared to the landfilling costs of €134,- per ton (CBS, PBL, RIVM & WUR, 2005). This is an added loss over the loss of material. The energy regeneration through incineration of waste was discovered to be 23.05 MJ per full carpet tile at a cost of 68.87 MJ of Gross Energy Requirement costs. With the regeneration of 23.05 MJ per carpet tile, per ton of product, a potential of 20 GJ can be achieved. At a consumer price of 0.0558 € per kWh excluding taxes, transportation fees and other charges, this equals a potential of €310,- in regained energy per ton of carpet tiles. It must be noted that the costs of energy for businesses (and in particular industries) are much lower than the 5.6 cents per kWh a consumer pays. These gains are also not for the carpet manufacturer, but rather are for the incineration plant. In other words, there are no financial gains of incineration over landfilling for the carpet industry other than a possible savings in disposal costs per ton of material.

Planet

Where the environmental costs of landfilling are to be calculated across a great time span, the environmental costs of carpet tile incineration are almost simultaneously. Incineration plants in the Netherlands are to adhere to strict regulations in regard to emissions, and through filters a lot of harmful emissions can be capsulated and possibly converted. This makes incineration a better alternative in terms of greenhouse emissions. Incorporating the emissions saved through energy regeneration, the emissions of incinerations are estimated to be 46 grams of CO_2-equivalents per kg waste. For landfilling, this equals 500 grams of CO_2-equivalents per kg waste. Move over, valuable land space is saved through incineration compared to landfilling.

Duration

The implementation of creating carpets suitable for incineration is dependent on both the incineration plants as well as the carpet manufacturers. As claimed, the bitumen backing of carpets pose a primary issue for incineration. A transition from bitumen to alternative backing materials is expected to be easily implemented, as Interface already offers a line of bitumen-free carpet tiles. Assuming this to be the only limitation of the incineration plants, and assuming as per now the carpet industry focusses on the production of incineration-compatible backing material, the implementation span of EOL carpet incineration is estimated to last one lifetime of carpets, so ranging between 10 and 15 years.

Effect

Based on the assumption of 20 GJ energy regeneration through incineration, and the ability to incinerate carpets, without the decreased transportation distance, the following effects were calculated:

Table J4

Effects of EOL carpet incineration with heat and energy regeneration

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.7	TOTAL	4.8
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-2.2%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.0	TOTAL	57.5
Virgin	72.1	RL	1.1	Backing sep.	0.0	Change	-26.3%
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	-20.5		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	29
Manufacturing	11	RL	4	Disposal	9	Change	45.4%

In terms of GHG-emissions, a saving of 2.2% in emissions can be achieved through incineration of EOL carpet tiles instead of landfilling them, at the costs of 45% increase in PM_{10} emissions. Bigger savings can be realized in terms of energy. Although 63.5 MJ worth of material is disposed, 20.5 MJ is regenerated by incineration. On a total cost of 78.672 MJ, 20.5 MJ regeneration equals an energy savings of 26.3% compared to the nil-alternative.

Uncertainty

Although the exact composition of materials and the energy effects are somewhat uncertain, as is the ability to process carpet tiles, the technology of waste incineration is widely proven and relatively basic. As such there is little uncertainty but small deviations from above discussed energy regeneration figures and incineration emissions. It is thus considered a stable solution.

Conclusion

Offering EOL carpets for energy regeneration incineration is calculated to provide a noticeable reduction in emissions as well as energy requirement for the entire supply chain. But this scenario proved to be unrealistic, as Dutch carpets are not accepted by incineration plants due to their high combustion value. Changing the material composition could affect the acceptance of carpets for incineration. The costs of supplying material for incineration are also a reduction from the costs of landfilling, the current option, thus there are possible financial gains for the manufacturer by altering the backing material composition. This backing layer has proven to be a big source of the issue in earlier studies, but alternatives for these tiles are yet to be widely adapted by both customers and the industry.

J.2.2 Downcycling to Fiber Reinforced Concrete (FRC) fix

As for recycling/downcycling purposes of EOL carpet tiles, options are limited. One of the uses for end-of-lifecycle carpets widely discussed in the literature is the use of fibers in concrete. Applying (nylon) fibers in concrete in a mixture of 0.5%-2% fibers to concrete creates Fiber Reinforced Concrete, FRC in short. This FRC is able to endure more strain in different scenarios (Wang, 1999). A full description of the advantages and disadvantages of FRC can be found in appendix D.3.2. FRC only uses the nylon fibers, so after separation of backing material from the top layer, the backing layer has to be disposed of, where the nylon fibers are downgraded to form concrete.

What

Downcycle nylon from EOL carpets to strengthen concrete.

How

After shredding of the EOL carpet, the nylon fibers are downcycled to the creation process of concrete. These fibers (0.5%-2% of the total weight of concrete) are mixed in with the concrete before the pouring and curing process.

Profit

FRC is not a commonly used method of reinforcing concrete in the Netherlands. More so, FRC limits the ability of the concrete to be recycled afterwards (Naqvi et al., 2018). With limited usage and reduced circularity, FRC is not a widely sought after product. For the carpet manufacturer, the downcycling of EOL carpets to FRC requires the separation of nylon top layer from the backing material. The separated pure nylon fibers can be repurposed in FRC. The main financial gain to this alternative is in the limitation of disposal fees. Including the separation costs, but not assuming a market value for these EOL product, the carpet manufacturer gains roughly €0.06 per carpet tile using this alternative.

Planet

In terms of circularity, FRC is just a shift of the problem. The lifespan of concrete is more than the lifespan of a carpet tile and as such it might prove a temporary solution to landfilling. But at the end-of-lifecycle of this fiber reinforced concrete, it poses less recycling purposes due to the fact it is contaminated with nylon fibers (Naqvi et al., 2018). The usage of high value resources like nylon in a low value product as concrete makes for more skepticism on the environmental aspect. This alternative does not limit the use of virgin resources but rather offer another disposal method to an otherwise recyclable resource.

Duration

All materials and equipment required to make FRC are currently available to carpet and concrete manufacturers. This alternative can be directly implemented.

Effect

Calculated for FRC with a 2% fiber content (maximum strength), assuming full demand for EOL nylon fibers by the concrete industry, the following effects were calculated:

Table J5

Effects of FRC production from EOL carpet tile

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	4.6
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-5.4%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	77.9
Virgin	72.1	RL	1.1	Backing sep.	0.0	Change	-0.1%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-0.2		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	1	TOTAL	20
Manufacturing	0	RL	4	Disposal	0	Change	2.6%

One full carpet tile has the ability to be turned into 15 kg of FRC, possibly saving 0.016 MJ per kilogram FRC. This makes for a very limited amount of energy saved, when factoring in the energy costs of separating the backing material from the top layer. In the short term, emission wise, a bigger result is achieved by reducing the emission of greenhouse gasses by roughly 5.4%, primarily through avoided disposal costs. But as discussed in chapter D.2.2 this causes only a delay of environmental effects, if not an increase. As the model does not incorporate the effects of EOL FRC, it gives a misrepresentation of climate effects.

Uncertainty

There rests little uncertainty in the recycling options for FRC. Changes in recycling technology could make FRC more recyclable. However, the costs of recycling nylon fibers after usage in FRC are deemed much higher than the recycling costs of pure uncontaminated nylon fibers. Demand for FRC is however one of the decisive factors on the possible success or failure of this downcycle method.

Conclusion

FRC is more of a disposal method rather than a downcycling method for nylon fibers. The positive environmental effect of downcycling nylon fibers to FRC is primarily caused by limiting the weight of landfilling. The energy savings are marginal as the costs of separating are almost equal to the costs of creating concrete. This alternative renders the nylon fibers unfit for later recycling, thus scoring negatively on circularity, as well as making the concrete unfit for recycling. For FRC, carpet tiles are to be shredded and the nylon fibers are to be separated from the backing material. One is left to question why this high value resource would then not be processed into new nylon but rather be used in a low value product. This method of recycling is thus deemed inefficient.

J.2.3 Downcycling into insulation fix

Through the process of creative thinking another possible solution for EOL carpets was found in house insulation. It is not uncommon to see mountain cabins insulated with wool in Scandinavia. Research indicates that nylon has equal or slightly lower insulating properties (Holmér, 1985). Mainly used for electrical insulation, this scenario explores the usage of nylon fibers for home insulation. It is assumed to be a replacement for rock wool, a commonly used material applied between drywall for insulating houses.

What

Providing pure nylon fibers as way of insulating a house.

How

Pure shredded nylon fibers are deposited between drywall and the outer wall of a building, naturally forming pockets of air between themselves.

Profit

The primary downside of nylon 6 as insulation material was listed in research by Alam, Singh & Limbachiya (2011) as being too costly. An own cost calculation was conducted based on current retail prices. Rockwool will cost around €3,- per 0.04 m^3, making for 100€ per m^3. The average density of nylon-6 is 1.31 g/cm^3. Assuming air is needed for insulation purposes, we assume a nylon to air ratio of

50:50 for one unit of insulating nylon. This assumption equals a requirement of 655kg of nylon to form one cubic meter, requiring 1908 carpet tiles. This requires a retail price of little over €28.000,- in EOL carpets. The mere energy costs of separating the nylon fibers of 1908 carpet tiles equals (0,1652 MJ/kg * 2199 kg) 101 kWh. At 20 cents per kWh, the separation of fibers costs a fifth (€20,20) of rockwool. It then requires transportation costs, as well as specialized material for application. On the other end of the spectrum: diverting 1908 tiles worth of nylon fibers from landfilling does save a rough €90,- in landfilling costs. It is then concluded that there might be financial gains to be had converting EOL carpets to insulation material, regardless of the sell price of these fibers to insulation companies.

Planet

Compared to the FRC alternative, this alternative has the added benefit of not processing the nylon fibers. This means that in terms of resource leaks, in this alternative a nylon fiber holds its value: it is unprocessed and can be reclaimed and repurposed at any time. It furthermore has the added benefit of being used in a way to improve the sustainability of a building, that even more energy is saved through the prevention of lost heat. It does however not limit the dependency on virgin resources or downcycled resources for the carpet industry, as the fibers are not used in the creation of new carpets.

Duration

The equipment is already available. Application of nylon fiber insulation could be based on current insulation alternatives like seashells, which are blasted into place via compressor and a material supply. The insulation properties of nylon are to be more extensively tested, as well as the best material composition. For this, a two year research period is suggested. Thus, the implementation of nylon-fiber insulation is assumed to be within 3 years.

Effect

Based on the previously mentioned assumptions, and on the energy requirement of 17.5 MJ/kg rockwool produced (Duijve, 2012, p.26) at 3.17 kg CO_2-equivalent/kg rockwool (Duijve, 2012, p.29) the following effects were calculated:

Table J6

Effects of insulation production from EOL carpet tile

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.5	TOTAL	3.71
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-24.4%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	-1.0		
Manufacturing	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.2	TOTAL	72.8
Virgin	72.1	RL	1.1	Backing sep.	0.0	Change	-6.6%
Closed	0.0			GER disposed	21.4		
Open	0.0			Effect	-5.3		
Manufacturing	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	1	TOTAL	20
Manufacturing	11	RL	6	Disposal	0	Change	3%

Compared to the FRC alternative, recycling of nylon fibers through insulation shows a bigger decrease of both energy requirement as well as emissions. The saved emission costs of disposal are still one of the primary forces behind the reduction in greenhouse gasses, but a kg of CO_2-equivalents is saved by eliminating the need of producing rockwool. The energy requirement of shredding and separating nylon fibers is also notably smaller than that of the production of one unit of rockwool. Thus 5.3 MJ reduction of energy is achieved by using nylon fibers instead of rockwool, making for a total energy savings of roughly 6.6%.

Uncertainty

This calculation is based on several assumptions which are improperly researched. It does serve as a rough exploration of the option of using nylon fibers for construction insulation purposes. It would require more investigation and tests in order to conclude if nylon, as proposed, is an effective method of insulating a building.

Conclusion

Using nylon fibers as insulation looks a promising solution and repurposing method. The costs of preparation of these nylon fibers is relatively low in terms of energy requirement, CO_2-eq. emissions as well as on a monetary front. The application of nylon fibers for insulation has the potential to be relatively easy. Although it does not eliminate the need for virgin resources in the creation of carpet tiles, the nylon fibers retain their logistic value in the application as insulation material. It does not offer a use for the backing material, which will end up being landfilled. But in terms of sustainability, nylon fiber insulation scores higher than the FRC alternative. This all is based on the findings that nylon offers good insulation and thus could be applied in for instance house insulation. Lastly, this alternative offers a potentially better solution to the capacity problem. A lot more carpets are needed to produce one unit of nylon insulation than that are needed to produce one equal unit of FRC. With equal demand for FRC and Nylon-6 insulation, the insulation alternative offers a better solution for EOL carpets as it allows for a bigger volume to be repurposed.

J.2.4 Full circularity fix

As discussed multiple times, the backing material has proven to be the biggest issue in regards of recycling. The separation of all layers/materials of backing material are either too costly, too inefficient, or simply technically not achievable. From this problem, the need of a sustainable backing material is often expressed. This scenario approaches the costs of full circularity. There are a few noticeable assumptions that make this an unlikely scenario. First and foremost, as recycling costs of all backing materials are unknown (as they are not being recycled anywhere), it is assumed that the energy required for recycling the backing material is equal to the energy required to recycle the nylon face fibers. In this scenario, the 12% loss of material through usage is considered to be supplemented by downcycled resources.

Technically, based on the findings by the Deutsche Umwelthilfe (2017, February), everything in the Touch & Tones could be recycled and be reused for the same purpose in new carpets. However, energy requirements for this recycling effort are unknown and extreme hard to find. Thus, this scenario assumes energy requirement for the recycling of backing material. For the energy requirement of recycling of backing material, the exact same energy requirement from nylon-6 is used, set at 0.264 MJ/kg backing material. It also assumes that the chalk is recycled as well. The effect of higher recycling energy requirements is modelled too, posing an interesting conclusion.

What

Every carpet tile is fully recyclable into new carpet tiles.

How

In this scenario, through shredding, all materials are separated, collected, and repurposed into new resources used for the exact same application in new carpets.

Profit

As the exact repurposing costs are unknown, it is hard to reach a conclusion on the profitability of such an operation. Experts argue that the recycling of all materials is extremely costly and thus landfilling is preferred by the manufacturers (Miraftab et al., 1998; Realff et al., 2005; Miraftab & Mirzababaei, 2009). Profitability is then also highly dependent on the availability of the virgin resources, as high resource prices could make for recycling to be cheaper than acquiring virgin resources. If a redesign of material/manufacturing is required, machinery has to be adapted or even created, increasing the costs. However, these costs are claimed to be compensated by the government (de Baedts, 2012, may).

Planet

In terms of environmental stress, eliminating the requirement of virgin resources is one of the best ways to reach sustainability. For carpet tiles however, circularity cannot be achieved. Estimates by the carpet manufacturer assume 12% of material loss through usage (Bossenmayer et al., 2019, January). These are for instance nylon fibers that come detached from backing and stick to someone's shoe. This loss of material is to be compensated. It can be argued that you would then use 1.12 EOL tiles to produce one new carpet tile, but this would cause a deficient at the end when the stock of EOL tiles runs out. Thus, there will still remain a need for 12% of virgin or downcycled resources.

Duration

Interface and Tarkett/Desso strife for circularity at least since 2007 (Lampikoski, 2012; Tarkett, 2015, January; Interface, 2019, April). Both have concluded this effort has failed, based on the current product line. It is thus assumed that carpets have to be redesigned, in particular the backing and these materials. Redesigning the manufacturing process could take a while, it then has to be adapted by the manufacturer. It is assumed that this transition could take up to a few years. From that point, fully circular carpets can be produced and sold, but it will last up to one lifecycle of carpets before all bitumen-backed carpet tiles are removed from usage and are replaced with recyclable carpets. During the production of this first generation of recyclable carpet tiles, there is not a full supply of EOL material. Thus, at the start of the second lifecycle enough resources are regained to manufacture a carpet tile out of recycled material. Meaning this operation will last an absolute minimum of 10 years plus the time it will take to introduce the recyclable carpet onto the market.

Effect

As expected, using no virgin resources has a major effect on the total emissions and energy requirements. The tables below display the results of set 88% closed-loop recycled resources, and 12% downcycled resources to compensate the loss of material, at the costs of 0.264 MJ/kg nylon 6 and backing material recycling.

Table J7

Effects of full circular carpet tile production

Emissions [kg CO$_2$-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	0.417	Transp.	0.136	Disposal	0.000	TOTAL	0.914
Virgin	0.400	RL	0.120	Nylon sep.	0.011	Change	-81.261%
Closed	0.017			Backing sep.	0.012		
Open	0.000			Effect	0.000		
Manufacturing	0.218						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	8.199	Transp.	1.306	Nylon reclaim	0.169	TOTAL	14.476
Virgin	7.927	RL	1.149	Backing sep.	0.190	Change	-81.436%
Closed	0.272			GER disposed	0.000		
Open	0.000			Effect	0.000		
Manufacturing	3.462						

Emissions [milligram PM$_{10}$ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	1	TOTAL	23
Manufacturing	12	RL	4	Disposal	0	Change	15%

As expected, the costs of energy and emissions is spectacularly decreased when the need for virgin resources is marginalized. The energy costs of recycling are very low in this calculation. It does however allow for limited conclusion as the scenario is less than likely and based on unrealistic assumptions.

During a stress test, an approximation of break-even costs was sought in terms of energy requirement. This analysis resulted the insight that recycling cost of 80 MJ/kilogram backing material (roughly 300 times the energy amount as used by the model run) still make for an increase in sustainability (at -1.8% kg CO_2-equivalent costs and -7.7% MJ energy requirement). In other words: the recycling of the carpet can be 300 times as high as the costs for recycling nylon and it will still remain profitable in terms of emissions and in terms of sustainability.

Uncertainty

As discussed, there is high uncertainty as circularity can be achieved through the usage of a plethora of different resources, recycling methods and energy sources. This calculation is nothing more but an exploration of one of the more optimal scenarios.

Conclusion

Theoretically, circularity can be achieved based on the current material composition (Deutsche Umwelthilfe, 2017, February). All materials are fully recyclable into the same function they originated from. This is however financially non-viable, and would require a lot of energy. This is confirmed by Oudenbroek to be one of the main reasons why Interface halted their effort to recycle complete carpet tiles (E. Oudenbroek, personal communication, November 02, 2020). This was found to be surprising and posed a conflicting image, as durability tests of the model indicate that the costs of recycling backing material can be up to two hundred times as expensive as the recycling of the nylon top fiber, and it would still make for emission and energy savings.

The exploration into the effects of circularity gave expected results: eliminating the need of virgin resources, combined with the low effort of recycling EOL carpets into new carpets, make for highly reduced resource and emission demands. In terms of energy, the exact energy required to recycle all materials is unknown. But based on the findings, there is a huge margin of energy usage by machinery to recycle all backing materials into new resources except limestone. With relatively many unknowns however, little insights are gained but for the conclusion that full circularity cannot be achieved for the carpet industry as material is lost through the lifespan of the material, which will have to be complemented either from virgin resources or by downcycling (or even upcycling) from other material.

J.3 PRODUCTION LEAKS

Finally, there are resource leaks that occur during the production. This ranges from the resources used to produce one carpet tile to the energy sources that are used during production. This section discusses ways to reduce the emissions and energy requirements of everything that has to do with how a carpet tile is produced, restrained by the demarcation as presented in chapter 2.4.

J.3.1 Zero-emission manufacturing fix

The manufacturing process is where the resources are converted into a carpet tile. This conversion requires mainly electricity for the heavy machinery to operate. Historically, a lot of focus was paid on making the manufacturing process as sustainable as possible. This scenario explores the effect of using only zero-emission renewable energy for the manufacturing of carpets.

What

Have a zero-emission energy source for the production of carpets.

How

Generate electricity used by the machinery locally and through renewable energy sources such as solar power or through wind energy harvesting.

Profit

In terms of profit per carpet, energy savings will be marginal. The creation of one carpet tile was researched to cost 2.59MJ, or 0.7194 kWh, at 20 cents per kWh that makes for an energy cost of 14 eurocents. However, using renewable energy sources is still subsidized by Dutch government, thus limiting the investment costs. A rule of thumb for the consumer market is that a photo-voltaic (PV) panel break-even point is reached at 5-7 years of operation. For industries, this lifespan might be longer as energy costs per unit are lower. For wind energy, it is less plausible to invest in a private wind turbine due to the investment costs and capacity required.

Planet

The topic of sustainability in regard to energy is a controversial one. The creation of a PV-panel or wind turbine is marked by a reliance on rare earth minerals. In particular solar panels have a limited lifespan and not all parts are recyclable. These costs have to be calculated in the price of one unit of energy. However, these costs are subject to high uncertainty. For instance, the lifespan of a solar inverter is a high uncertainty and could affect the costs per unit energy greatly, as is the amount of energy generated. It was opted to use the average emission factors as identified by the highly respected Intergovernmental Panel on

Climate Change. This means that zero-emission energy sources are in fact not entirely producing energy free of emissions, thus a cost will arise for energy.

Duration

Installation of PV-panels and batteries is dependent on the workforce but should not take longer than 3 months.

Effect

The following effect was observed:

Table J8
Emission effects of zero-emission energy sources

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	3.6	Transp.	0.1	Disposal	0.8	TOTAL	4.7
Virgin	3.6	RL	0.1	Nylon sep.	0.0	Change	-3.5%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Manufacturing	0.0						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS total	72.1	Transp.	1.3	Nylon reclaim	0.0	TOTAL	78.0
Virgin	72.1	RL	1.1	Backing sep.	0.0	Change	0.0%
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Manufacturing	3.5						

Emissions [gram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	9
Manufacturing	0	RL	4	Disposal	0	Change	-54%

The requirement for virgin resources remain unchained as they are externally gathered. As is the general energy requirement, as only the emissions per GJ have changed. The effect of this single modeling parameter is about 3.5% on the total emissions of the cradle-to-grave lifecycle. In terms of particulate matter, over 50% reduction of emissions is created by switching from natural gas to solar power.

Uncertainty

As discussed in chapter 6.3, there is uncertainty in regard to emissions of renewable energy sources. Furthermore, the compensation of supplying green energy to the net is uncertain and could change over time when more (or less) green energy is generated.

Conclusion

With a large surface for solar panels, and with a financial stimulus from the Dutch government, it seems to be beneficial to equip the manufacturing plants with a private zero-emission energy mean like PV-panels. It is however disputed that this measure could be achieved, as the manufacturing process is a continuous operation, and PV-panels only supply power when it is light out. This would mean that the plant is to remain attached to the national grid and have a general energy contract. This requires the carpet manufacturer to pay fees for the usage of the energy lines. Although it is at the moment still profitable to supply the grid with power instead of taking it, this could change. However, at current price levels and governmental support, equipping a manufacturing plant with PV-panels has the ability to both reduce emissions as well as make a profit in the long term. It is thus advised to further explore or consider this option.

J.3.2 Zero-waste manufacturing fix

Not all carpets produced end up being shipped to a customer. Carpet tiles are produced on spools and are cut into size. During this cutting process some material is lost, known as trimmings. These trimmings are determined to make up 1% of all resources. These trimmings are immediately disposed of. Also, misprints could be included in the lost material post.

What

Eliminate the waste during the manufacturing process of carpets.

How

Tuft carpets onto tile backings instead of spools and trimming afterwards. Also prevent misprints or production errors as best as possible.

Profit

Any product that is produced and processed that does not end up at a customer is in theory a loss of profit. The profitability of eliminating this waste is highly dependent on the measures needed to stop this waste, as well as the costs of resources that are used in the creation of this waste. Without insights in the exact production method, it is deemed likely that any “easy fix” in regard to resource leaks has already been fixed, also in sight of the manufacturer’s declarations of sustainability (Bossenmayer et al., 2019, January). It is thus assumed that there are no short-term profits to be achieved by further eliminating waste, and highly costly changes are required to further eliminate this productional waste.

Planet

As for profit, the environmental impact of waste/trimmings is an absolute loss in the fact that it serves absolutely no purpose. And without any recycling method, for every 25 m^2 carpet produced one carpet tile is disposed, which is still a loss worth trying to fix. Fixing the resource leak on productional waste would limit requirement of virgin resources, thus positively impacting the environment. It must be noted that limiting waste is a tool in this approach, rather than an objective. In other words: it might not be worth wile to invest in a very energy insufficient machine to slightly reduce the productional waste, as it mitigates the gains of limited resources loss by consuming more energy e.g..

Duration

Highly dependent on the production method and possible fixes. Could range from other cutting tools (implementation time of weeks to a few months) to changing the entire production process (years).

Effect

The production of material that is immediately discarded equals $3{,}60\times10^{-2}$ kg CO_2-equivalent units in wasted resources and energy, or $7{,}13\times10^{-2}$ MJ, equaling close to 1% of the total emissions.

Uncertainty

Uncertainty lies in the methods that can be used to further limit the waste and in the costs of resources that are wasted.

Conclusion

The emissions that can be saved by eliminating waste are really slim, simply because the productional energy costs are not that high. This can however be offset when virgin resource costs rise, making the product more valuable. Although it is always advisable to seek ways to limit productional waste, given the small change when all waste is eliminated and the fact that there is already relatively little waste produced, it might be more efficient to seek other ways to increase sustainability.

J.3.3 Zero-emission recycling fix

As discussed before, the costs of virgin resources are external. The carpet industry is not responsible for, for instance, the creation of caprolactam, which is used for the creation of Nylon-6 fibers. Thus, it might be more difficult to change the emissions of the gathering of these resources. However, the carpet industry could be in charge of the methods of recycling. This model run simulates a zero-emission recycling effort, meaning that processing EOL carpet tiles to usable resources emits close-to zero emissions.

What

The recycling of EOL carpet tiles is fully climate-neutral.

How

Generate the electricity and possibly other resources needed for the recycling effort fully sustainably and zero-emission.

Profit

The financial benefits to having zero-emission recycling are as discussed in appendix J.3.1, where the costs/profits of zero-emission production are discussed. This alternative adheres to the same principles.

Planet

Emissions of the recycling effort are prevented in this scenario. The total effect on the environment is however deemed dependent on the method of energy generation. As discussed earlier, there are downsides to owning PV-cells in terms of sustainability. All these effects are to be kept in mind when looking at the mere results of this model run.

Duration

The duration of implementation of zero-emission recycling is a combination of factors as discussed in appendix J.3, and is deemed to be achievable in a relative short term.

Effect

Without changed parameters in regard to EOL recycling, the effect of zero-emission energy on recycling is merely a limitation in emissions of the downcycling of nylon 6 into carpets. As this downcycling cost is already not present in the nil-alternative scenario, no parameters change. In the case of full nylon fiber recycling (FRC), switching to solar panel powered energy from natural gas saves 9×10^{-3} kg CO_2-equivalent units.

Uncertainty

If the recycling effort requires more energy, this scenario makes for a decrease of emission costs. The amount of recycling energy needed is the uncertain factor in this scenario. This is equal to the uncertainties as discussed in appendix J.3.1.

Conclusion

Transitioning to renewable zero-waste energy sources for recycling has, as expected, only a very marginal effect. This effect will increase once at the EOL stage carpets are shredded and prepared for other uses. Also supplying these machines with zero-emission energy will positively affect the emissions of the entire supply chain. Again, a caution is issued in regards of the results of this model in terms of zero-emission energy: this is not calculated including the emissions for e.g. the costs of a PV-panel.

J.3.4 Zero-emission resources fix

The final option that is explored in reaching a more sustainable carpet tile is through the elimination of emissions at the resource stage. In this simulation it is assumed that all resources for the production of a carpet tile are mined emission-free. Although not realistic in the current scenario, a zero-emission recycling method combined with full circularity as previously suggested could theoretically be able to produce raw resources for carpet tiles without producing any greenhouse gasses. This scenario calculates the effect by assuming the virgin resources are mined without any production of GHGs.

What

All virgin resources required for the production of carpet tiles are fully climate-neutrally mined.

How

Through either closed-loop recycling or open-loop recycling, combining a zero-emission energy source for the preparation of new usable resources, or through the adaptation of zero-emission mined virgin resources.

Profit

The adaptation of zero-emission energy sources can be, as discussed, relatively cheap or even be cost-efficient. The energy requirement however could increase with the elimination of for instance fossil fuels, as some processes might have to be changed to facilitate the zero-emission policy. The costs of such an operation are highly dependent on the changes that are to be made to the acquiring and processing of resources, and thus a good cost indication is hard to estimate. However, investment costs in excess one million euro are deemed unquestionable.

Planet

This scenario has two sides to the story. On the one hand, it assumes full circularity, which would eliminate the need for virgin resources, thus limit the strain on the earth's exhaustible resources like oil (needed to make the bitumen backing). On the other hand, if the virgin resources can be mined at zero emissions, the model assumes this to be a good alternative in terms of emissions. Luckily, the offset between recycled and virgin resources will show in the energy requirement.

Duration

The implementation of a fully zero-emission mining/creation process of Nylon, bitumen, polyester, polypropylene, limestone, aluminum hydroxide and glass fiber are estimated to take tens of years, if it will prove to be achievable at all.

Effect

The (unrealistic) scenario of eliminating all costs attached to the creation of resources is huge. The following table shows the effect of having zero emissions in the gathering for any resources used in production, as well as eliminating emissions in the preparation of the resource for recycling.

Table J9

Emission effects of zero-emission resource production

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS tot	0.0	Transp.	0.1	Disposal	0.8	TOTAL	1.2
Virgin	0.0	RL	0.1	Nylon sep.	0.0	Change	-74.7%
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Energy	0.2						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	9
Manufacturing	0	RL	4	Disposal	0	Change	-53.9%

Emissions [gram PM10 per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	9

Manufacturing	0	RL	4	Disposal	0	Change	-53.9%

Although this scenario is deemed completely unrealistic, it does provide insights into the effect of virgin resources on the total emissions of the system.

Uncertainty

The main uncertainty is how (financially) viable it is to produce/mine all resources without any emissions. For instance, the limestone needed for the carpet tiles is often mined in quarries, requiring heavy machinery which are fueled by diesel, or even require explosives which create a dose of CO_2 through combustion. Through closed-loop circularity however, zero emission recycling of the resources is more likely an achievable goal but would still require a lot of changes in the production process and rely technological advances.

Conclusion

Eliminating the emissions of all processes that are fixed to the generation of resources is a great way to increase the sustainability in terms of limiting emissions. It does require technology that could increase the energy usage. It is thus the question where a break-even point occurs in emissions saved at the costs of energy. This break-even point is both financially of importance as well as important in terms of the sustainability. If a zero-emission resource supply is established by achieving full closed-loop circularity, the environmental strain is highly affected. If a zero-emission resource supply is established by altering the mining processes of the virgin resource flow, the environmental strain remains equal in terms of exhaustion of the earth’s resources. It is thus highly dependent on the available (technological) solutions to supply zero-emission resources. But the technical feasibility remains questionable.

K VALIDATION

K.1 KEY DATA

K.1.1 Specifications of the carpet tile

Table K1

Carpet dimension and weight specification

Length	50 cm
Width	50 cm
Height	1.06 cm
Weight	1152.5 gram
Volume	2.65×10^{-3} square meter

Table K2

Gross energy requirement and emission per resource

Resource	Required [kg]	GER [MJ/kg]	Source	GWP [kg CO_2/kg]	Source
Polyamide 6	3.43×10^{-1}	137.6	CE Delft & RvO, 2018	9.1	CE Delft & RvO, 2018
Polyester	1.84×10^{-2}	380	Hammond et al., 2008	3.4	CE Delft & RvO, 2018
Polypropylene	1.27×10^{-2}	95.4	Hammond et al., 2008	2.0	CE Delft & RvO, 2018
Limestone	4.22×10^{-1}	0.85	Hammond et al., 2008	0.01	CE Delft & RvO, 2018
Aluminum hydroxide	1.05×10^{-1}	10.5	CE Delft & RvO, 2018	0.66	CE Delft & RvO, 2018
Polymer dispersion	5.30×10^{-2}	79.3	CE Delft & RvO, 2018	3.3	CE Delft & RvO, 2018
Modified bitumen	1.79×10^{-1}	53.9	CE Delft & RvO, 2018	0.59	CE Delft & RvO, 2018
Glass fibre	1.38×10^{-2}	41.9	CE Delft & RvO, 2018	2.4	CE Delft & RvO, 2018
Additives	5.76×10^{-3}	*	*	*	*

* = data unknown

For “additives”, no specification was found in any of the literature, meaning the exact material composition and emissions of these additives is unknown. It is as not included in the total emission calculation, but is kept part of the total weight of a carpet tile.

K.1.2 Production method and energy

Table K3

Energy requirement per production stage

Process	MJ/tile	Source
Nylon fiber production	0.59	Sim & Prabhu, 2018
Backing + completion	1.92	Sim & Prabhu, 2018
Nylon dyeing	0.94	Li, 2007

Table K4

GWP and PM_{10} production per energy source

Type of energy	GWP [kg CO_2-eq./GJ]	Source	PM_{10} emission [kg PM_{10}/GJ]	Source
Solar	13.3	Bruckner et al., 2014	0.0	Hammingh et al., 2010
Wind	3.1	Bruckner et al., 2014	0.0	Hammingh et al., 2010
Geothermal	10.6	Bruckner et al., 2014	0.0	Hammingh et al., 2010
Hydropower/ocean	6.7	Bruckner et al., 2014	0.0	Hammingh et al., 2010
Biomass	109.6	Vreuls & Zijlema, 2009	155.0×10^{-3}	Nielsen et al., 2019
Petroleum	71.9	Vreuls & Zijlema, 2009	25.2×10^{-3}	Nielsen et al., 2019
Natural gas	63.1	Vreuls & Zijlema, 2009	0.9×10^{-3}	Nielsen et al., 2019
Coal	94.0	Vreuls & Zijlema, 2009	7.7×10^{-3}	Nielsen et al., 2019
Nuclear	3.3	Bruckner et al., 2014	0.0	Hammingh et al., 2010

K.1.3 Transportation

Table K5

Overview transport modes

Mode	**Specification**	**GWP [g CO_2-eq./tkm]**	**Energy req [MJ/tkm]**	**PM_{10} [g PM_{10}/tkm]**	**Max Load [carpet tiles]**
Car	Gasoline	344 [1] [3]	2.7 [4] [5]	0.115 [5] [8]	188 [10]
	Diesel	328 [1] [3]	2.4 [4] [5]	0.128 [5]	188 [10]
	LPG	280 [1] [3]	2.5 [4] [5]	0.115 [5] [8]	188 [10]
	Electric	187-328 [1] [2] [3]	0.6 [4] [5]	0.115 [5] [8]	188 [10]
	Hybrid	360 [1] [3]	1.1 [4]	0.115 [5] [8]	188 [10]
	Hydrogen	187-328 [1] [2] [3]	1.2 [4]	0.115 [5] [8]	188 [10]
Van	Diesel	630 [3]	14.7 [9]	0.148 [9]	1,301 [11]
	Electric	359-630 [2] [3]	3.97 [9]	0.133 [8]	1,301 [11]
Truck	3-10t diesel	480 [3]	4.6 [9]	0.017 [5]	6,941 [11]
	10-20t diesel	300 [3]	2.8 [9]	0.017 [5]	14,004 [11]
	20-50t diesel	95 [3]	1.2 [9]	0.012 [5]	27,895 [11]
	3-10t Electric	274-480 [2] [3]	1.24 [9]	0.015 [5] [6] [7]	6,941 [11]
	10-20t Electric	171-300 [2] [3]	0.76 [9]	0.015 [5] [6] [7]	14,004 [11]
	20-50t Electric	54-95 [2] [3]	0.32 [9]	0.011 [5] [6] [7]	27,895 [11]
Train	Diesel	30 [3]	0.40 [9]	0.050 [9]	1,200,000 [12]
	Electric	25 [3]	0.15 [9]	0.000 [9]	1,200,000 [12]
	Combined	27 [3]	0.275 [9]	0.020 [9]	1,200,000 [12]
Barge	32 TEU	65 [3]	0.845 [9]	0.035 [9]	400,000 [12]
	96 TEU	60 [3]	0.6275 [9]	0.025 [9]	1,200,000 [12]
	200 TEU	60 [3]	0.380 [9]	0.013[9]	2,500,000 [12]

[1] Calculations, see appendix F.4.1.1
[2] Wietschel, Kühnbach & Rüdiger, 2019
[3] Stimular, 2011
[4] Howey, Martinez-Botas, Cussons & Lytton, 2011
[5] Den Boer, Brouwer & Van Essen, 2008
[6] Den Boer, Aarnink, Kleiner & Pagenkopf, 2013
[7] Green Truck Partnership, 2014
[8] Timmers & Achten, 2016
[9] Hoen, Den Boer & Otten, 2017
[10] BMW, 2020
[11] Mainfreight, 2020
[12] Bellmore, 2008

K.1.4 Recycling/downcycling/disposal

Table K6

Energy requirement EOL carpet separation

Process	MJ energy requirement per kg material [MJ/kg]	Source
Separating backing from nylon fiber	0.1652	Sim & Prabhu, 2018
Nylon fiber recycling	0.264	Sim & Prabhu, 2018

Table K7

Disposal costs EOL carpet tiles

Disposal option	kg CO_2-eq./kg waste	Source
Landfill	0.75	Arena et al., 2003; Manfredi et al., 2009
Incineration	0.643	Helftewes et al., 2012

Table K8

Material emissions of products that allow reuse of nylon fibers

Product	Resource cost [kg CO_2-eq./kg]	Source
Concrete	0.150	Liu, Ahn, An & Lee (2013)
FRC	0.147	Calculation
Rockwool	3.170	Duijve, 2012
Nylon insulation	0.000	Calculation

K.2 KEY DATA UNCERTAINTY

All of the presented key data come in a range of uncertainty. The presented key figures are based on nationally accepted sources, and are presented in a singular unit. As discussed in chapter 6.1, these figures come with a degree of uncertainty. Other researchers with other research methods might conclude on other results. And while using established averages is defendable, some information might get lost. If for instance some factors prove to be under- or overestimated, the results of the model could alter.

The list of key figures used in this thesis is too extensive to cover all ranges of uncertainty. This is why it was opted to divide the uncertainty into two categorizations: high uncertainty and low uncertainty. This classification is based on the findings within a category. For instance, in terms of material emissions, one research (Hammond et al., 2008) indicated that the emissions could exceed 40% more or less than the primary provided emission. Likewise, the research by Hoen et al. (2017, p.42) states that for vehicular emissions and energy requirements, a value deviation of maximum 10% covers the entire value range. This led to the creation of the following tables.

K.2.1 Uncertainty material emissions

Table K9

Uncertainty values raw materials - GWP

Resource GWP	-50%	initial value [kg CO_2/kg]	+50%
Polyamide 6	4.55	9.1	13.65
Polyester	1.7	3.4	5.1
Polypropylene	1	2	3
Limestone	0.005	0.01	0.015
Aluminum hydroxide	0.33	0.66	0.99
Polymer dispersion	1.65	3.3	4.95
Modified bitumen	0.295	0.59	0.885
Glass fibre	1.2	2.4	3.6

Table K10

Uncertainty values raw materials - GER

Resource GER	-50%	initial value [MJ/kg]	+50%
Polyamide 6	68.8	137.6	206.4
Polyester	190	380	570
Polypropylene	47.7	95.4	143.1
Limestone	0.425	0.85	1.275
Aluminum hydroxide	5.25	10.5	15.75
Polymer dispersion	39.65	79.3	118.95
Modified bitumen	26.95	53.9	80.85
Glass fibre	20.95	41.9	62.85

K.2.2 Uncertainty energy requirement production/recycling

Table K11

Uncertainty manufacturing processes energy costs

Energy requirement	-10%	Initial value [MJ/tile]	+10%
Nylon fiber production	0.53	0.59	0.65
Backing + completion	1.73	1.92	2.11
Nylon dyeing	0.85	0.94	1.03

Table K12

Uncertainty carpet tile separation and repurposing energy costs

Process	-10%	Initial value [MJ/kg]	+10%
Separating backing from nylon fiber	0.14868	0.1652	0.18172
Nylon fiber recycling	0.2376	0.264	0.2904

K.2.3 Uncertainty energy source emissions

Table K13

Uncertainty energy source GWP

Energy Source	-50%	initial value GWP [kg CO_2/kg]	+50%
Solar	6.65	13.3	19.95
Wind	1.55	3.1	4.65
Geothermal	5.3	10.6	15.9
Hydropower/ocean	3.35	6.7	10.05
Biomass	54.8	109.6	164.4
Petroleum	35.95	71.9	107.85
Natural gas	31.55	63.1	94.65
Coal	47	94	141
Nuclear	1.65	3.3	4.95

Table K14

Uncertainty energy source PM_{10}

Energy Source	-50%	initial value PM_{10} [g PM_{10}/kg]	+50%
Solar	0	0	0
Wind	0	0	0
Geothermal	0	0	0
Hydropower/ocean	0	0	0
Biomass	0.0775	0.155	0.2325
Petroleum	0.0126	0.0252	0.0378
Natural gas	0.00045	0.0009	0.00135
Coal	0.00385	0.0077	0.01155
Nuclear	0	0	0

K.2.4 Uncertainty vehicular emissions

Table K15

Uncertainty vehicular emissions - GWP

Mode	Specification	-10%	Initial value GWP [g CO_2-eq./tkm]	+10%
Car	Gasoline	309.6	344	378.4
	Diesel	295.2	328	360.8
	LPG	252	280	308
	Hybrid	324	360	396
	Hydrogen	168.3	187	205.7
Van	Diesel	567	630	693
Truck	3-10t diesel	432	480	528
	10-20t diesel	270	300	330
	20-50t diesel	85.5	95	104.5
Train	Diesel	27	30	33
	Electric	22.5	25	27.5
	Combined	24.3	27	29.7
Barge	32 TEU	58.5	65	71.5
	96 TEU	54	60	66
	200 TEU	54	60	66

Table K16

Uncertainty vehicular emissions – electric vehicles

		minimum (-43%)	maximum (diesel)
Car	Diesel	187	
	Hydrogen	187	328
Van	Electric	359	630
Truck	3-10t electric	274	480
	10-20t electric	171	300
	20-50t electric	54	95

Table K17

Uncertainty vehicular emissions – energy consumption

		-10%	Initial value Energy [MJ/tkm]	+10%
Car	Gasoline	2.43	2.7	2.97
	Diesel	2.16	2.4	2.64
	LPG	2.25	2.5	2.75
	Electric	0.54	0.6	0.66
	Hybrid	0.99	1.1	1.21
	Hydrogen	1.08	1.2	1.32
Van	Diesel	13.23	14.7	16.17
	Electric	3.573	3.97	4.367
Truck	3-10t diesel	4.14	4.6	5.06
	10-20t diesel	2.52	2.8	3.08
	20-50t diesel	1.08	1.2	1.32
	3-10t Electric	1.116	1.24	1.364
	10-20t Electric	0.684	0.76	0.836
	20-50t Electric	0.288	0.32	0.352
Train	Diesel	0.36	0.4	0.44
	Electric	0.135	0.15	0.165
	Combined	0.2475	0.275	0.3025
Barge	32 TEU	0.7605	0.845	0.9295
	96 TEU	0.56475	0.6275	0.69025
	200 TEU	0.342	0.38	0.418

Table K18

Uncertainty vehicular emissions – PM_{10}

		-10%	Initial value PM_{10} [g PM_{10}/tkm]	+10%
Car	Gasoline	0.1035	0.115	0.1265
	Diesel	0.1152	0.128	0.1408
	LPG	0.1035	0.115	0.1265
	Electric	0.1035	0.115	0.1265
	Hybrid	0.1035	0.115	0.1265
	Hydrogen	0.1035	0.115	0.1265
Van	Diesel	0.1332	0.148	0.1628
	Electric	0.1197	0.133	0.1463
Truck	3-10t diesel	0.0153	0.017	0.0187
	10-20t diesel	0.0153	0.017	0.0187
	20-50t diesel	0.0108	0.012	0.0132
	3-10t Electric	0.0135	0.015	0.0165
	10-20t Electric	0.0135	0.015	0.0165
	20-50t Electric	0.0099	0.011	0.0121
Train	Diesel	0.045	0.05	0.055
	Electric	0	0	0
	Combined	0.018	0.02	0.022
Barge	32 TEU	0.0315	0.035	0.0385
	96 TEU	0.0225	0.025	0.0275
	200 TEU	0.0117	0.013	0.0143

K.2.5 Uncertainty downcycling means

Table K19

Uncertainty downcycling costs/gains - GWP

	-10%	Initial value [kg CO_2-eq./kg]	+10%
Concrete	0.135	0.15	0.165
FRC	0.1323	0.147	0.1617
Rockwool	2.853	3.17	3.487

Table K20

Uncertainty downcycling costs nylon insulation - GWP

	Lower range	Initial value [kg CO_2-eq./kg]	Upper range
Nylon insulation	0	0	3.17

K.2.6 Uncertainty disposal means

Table K21

Uncertainty landfill costs - GWP

Disposal option	-50%	kg CO_2-eq./kg waste	+50%
Landfill	0.375	0.75	1.125

Table K22

Uncertainty incineration costs - GWP

Disposal option	-10%	kg CO_2-eq./kg waste	+10%
Incineration	0.5787	0.643	0.7073

K.3 EXTREME CONDITION TEST

During the extreme tests, the model is first examined how it behaves when all values are increased by a factor 100. The model did not break, but it was hard to measure how these results compare. It was thus opted to formulate hypothesis on how the model behaves when extreme data is used. The following section discusses the formulated hypotheses and their results.

K.3.1 Hypothesis 1: Increase in resource costs

The first hypothesis regards the costs of the system when the material requirement is increased. If the material requirement is increased, the total costs of the material should be increased in a similar amount. However, the total costs of the entire system, also the product of shipping emissions etc. is not to change by the equal factor.

The results indicate that a virgin resource requirement of 10,000% increases both the virgin resource emissions and energy requirements by 10,000%, but the total increase of emissions is lower due to the factors shipping and disposal remaining equal.

Verdict: The model behaves as expected

K.3.2 Hypothesis 2: Shipping costs and profitability downcycling

The second hypothesis is on the downcycling of EOL fishing nets as a source of downcycled nylon. This hypothesis assumes that for extremely high transportation distances for this downcycled resource, the production costs will outweigh the costs of virgin resources.

At 20.000 km transportation distance, the CO_2 and PM_{10} emissions still exceed the costs of virgin resources. At 100.000 km, the emissions are increased drastically.

Verdict: The model behaves as expected

K.3.3 Hypothesis 3: Shipping distance as a main emission factor

This hypothesis focusses on the aspect the transportation costs are (only) a part of the equation. Thus, if transportation costs are increased by a huge amount, the total system costs should not approach the same increase curvature, as other processes flatten this curve.

For this extreme condition test, a transportation distance of 200.000 km single trip with a 200% beeline conversion ratio was applied. This equals an increase of 487013%. For the GWP emissions, a total increase of 25557% was observed, which is as expected, as the shipping costs in the nil-alternative make up for 52% of the total emissions. The same upholds for energy requirement and MP10 emissions. The individual costs are increased, but the total costs are always the product of several processes and will prevent a distilled effect.

Verdict: The model behaves as expected

K.3.4 Hypothesis 4: No RL at no EOL material

This hypothesis assumes that the carpet tile through its lifecycle loses 100% of its weight. If it does so, there should be no reverse logistics movement and no costs should arise from the disposal of this carpet.

First results indicate a small disposal costs and GER disposed sum. This was due to the model assuming a 1% production loss that is included in the recycling/disposal stream. This provided two validations in one. First, the RL model section works, as no transportation movement and disposal emissions were calculated. It also proved that the material loss factor works too, not requiring any RL shipping.

Verdict: The model behaves as expected

K.3.5 Hypothesis 5: downcycling gains

The model did not include any economy of scale principles. Thus, a significant increase of supplied material to any downcycling or recycling process, is deemed to increase the costs/gains in an equal factor.

Although the model results are unreliable: it recycles more material than is possible to be recycled based on the product available, the costs scale equal to the increase of this downcycling process.

Verdict: The model behaves as expected

K.3.6 Hypothesis 6: transportation costs

The final to last hypothesis was in regard to transportation costs. It is expected that transporting zero weight over extreme long distances yields a high emission, as the vehicular movement causes a minimum of emissions.

Through the model, this minimum emission/energy requirement was not observed. The model thus failed on this validity test.

Verdict: The model behaves ***NOT*** *as expected.*

Exploration:

An explanation to this failed validity test can be found in the unit and calculation of the transportation emissions. By using tonkilometers, the overall emission of a vehicle is calculated through averages. Calculating the emission of a movement is then done by multiplying the tkm emission factor times the distance times the load. For the van, an emission factor of 630 grams CO_2/tkm was determined. Given the cargo of this van, in this scenario, being set at 0 carpet tile, or 0.00- ton, that makes for an emission of (630*0)=0 grams CO_2 per km. In comparison, a regular car emits anywhere from 175-225 grams of CO_2 per km. Thus, making this result rather unreliable and unrealistic. There should be a lower limit to these emissions which are not included in the model.

K.4 SENSITIVITY TEST

For the sensitivity test, all scenarios are replicated using the above stated uncertainty ranges of either 10% or 50%. The following results were obtained for each of the scenarios:

Table K23
Uncertainty effect on alternatives

Result	**Nil-alternative**	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**
GWP	+/- 46.1%	+/- 56.7%	+/- 48.6%	+/- 59.6%	+/- 48.9%
Energy	+/- 47.0%	+/- 60.3%	+/- 48.0%	+/- 50.3%	+/- 47.6%
PM_{10}	+/- 28.5%	+/- 30.5%	+/- 50.0%	+/- 50.0%	+/- 50.0%

The uncertainty impacts every alternative differently, as represented by the table above (Table K23). All absolute modeling figures were compared and the distribution of most-to-least favorable alternatives in terms of emissions was unaffected. It can thus be concluded that although uncertainty is able to impact the final GWP, energy requirement and PM_{10} emission figures, it does not affect the classification of best-to-worst performing

K.5 ENVIRONMENTAL PRODUCT DECLARATION VALIDATION

One of the closest approximations however to the real emissions of carpet tile productions are presented in the form of an Environmental Product Declaration, or EPD. For Interface's Touch & Tones 103, such EPD was issues to an independent bureau with full cooperation of Interface. Institut Bauen und Umwelt e.V. examined the total emissions from cradle to grave according to industry set standards in terms of independency. This presents an accurate view on the current emissions by the manufacturer of the carpet. Besides carpet tile details like weight and material composition, the model created was solely based on other, non-related sources. Thus, if the modeling results are in an acceptable range of the findings by the EPD, the model is more likely to prove valid and accurate.

The EPD of the product chosen as the standard is a great tool to validate some findings of the model, at least up to some extent. The EPD by Bossenmayer et al., (2019, January) gives an overview of the "global warming potential" of 1m^2 of Touch & Tones 103. This figure includes the raw material supply, creation of carpet tiles, transport, delivery, reverse logistics, waste management and disposal/reuse. Taking all these factors into account results in a global warming potential of 16.61kg CO_2-eq. per m^2, equaling 4.152 kg CO_2-eq. per carpet tile based on a 0% recycling rate. Replicating the conditions and assumptions of this EPD results in the following model run:

Table K24

Overview EPD statement modeling input

Production RSS		Production		Transport		Lifecycle		Reverse Logistic		Sorting	
Closed-loop	0%	PWR SRC	Natural gas	Distance	1400	Loss of Material	12%	Distance	1400	Recycled	0.00%
Open-loop	0%	Waste	1%	MODE	Truck + trailer (max 50t), diesel			MODE	Truck + trailer (max 50t), diesel	Downcycled	0.00%
Virgin	100%	Tot. Weight	1	# trips	1			# trips	1	Disposed	100.00%
										Disp. method	Landfill
										PWR SRC	Natural gas

With the following emissions and energy requirement as a result:

Table K25

Results EPD statement modeling simulation

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS tot	3.6	Transp.	0.2	Disposal	0.8	TOTAL	4.9
Virgin	3.6	RL	0.1	Nylon sep.	0.0		
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Energy	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS tot	72.1	Transp.	1.9	Nylon reclaim	0.0	TOTAL	79.2
Virgin	72.1	RL	1.7	Backing sep.	0.0		
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Energy	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	20
Manufacturing	11	RL	4	Disposal	0		

Compared to the 4.152 kg CO_2-equivalent by the EPD, this model returns a total emission of 4.912 kg CO_2-equivalent, an increase of almost 20% compared to the EPD, thus failing on the acceptable range. Closer inspection reveals a severe underestimation of the disposal costs by the EPD, which assumes that landfilling causes zero GWP. Applying this modeling decision to the model, by eliminating the disposal costs, the following results (Table K26) are achieved. Avoiding costs on disposal, the margin of error is reduced from 20% to 0.2%.

Table K26

Results EPD statement model run revised

Emissions [kg CO_2-equivalent per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS tot	3.6	Transp.	0.2	Disposal	0.0	TOTAL	4.1
Virgin	3.6	RL	0.1	Nylon sep.	0.0		
Closed	0.0			Backing sep.	0.0		
Open	0.0			Effect	0.0		
Energy	0.2						

Energy requirement [MJ per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
RSS tot	72.1	Transp.	1.9	Nylon reclaim	0.0	TOTAL	79.1
Virgin	72.1	RL	1.7	Backing sep.	0.0		
Closed	0.0			GER disposed	63.5		
Open	0.0			Effect	0.0		
Energy	3.5						

Emissions [milligram PM_{10} per carpet tile]							
Production		**Shipping**		**Repurposing**		**TOTAL**	
Open-loop	0	Transp.	5	Separating	0	TOTAL	20
Manufacturing	11	RL	4	Disposal	0		

With a 0.2% margin of error between the EPD declared GWP and the calculated GWP, the model's results lie within the realm of possible emissions. It is deemed within an acceptable range and by simply comparing units, this model is deemed possible, and perhaps even plausible. A cation is issued that the model is however different from the EPD as it does over- and underestimate some effects compared to the model. The model for instance uses a higher cost of disposal compared to the EPD, whereas the EPD assumes a higher cost of resources and manufacturing. Thus, it cannot be indisputably concluded that the model is valid, but based on the limited data, it can be concluded that the model performs well. This section also serves as a warning on the underestimation of the global warming effect of landfilling. As observed, landfilling costs amount to a third of the total emissions based on the sources through which this model was created. The assumption by the EPD to consider landfilling to be zero-emission is, based on these sources, thus disputed.

L SCORE CARDS

Through the model, several means are identified that have the ability to increase the sustainability of the carpet industry. However, the acceptance of these means is highly dependent on a plethora of criteria by the end user: the carpet industry. A multi-criteria analysis provides a framework to rate individual alternatives on a set of criteria. This multi-criteria analysis is constructed according to the book "Solving Complex Problems" by de Haan & de Heer (2012). These criteria are found through a literature study and annual reports from the main carpet manufacturers in the Netherlands. It is also validated by Oudenbroek, Vice President operations at Interface EMEA at a validation and feedback session arranged at 2nd of November 2020.

Within this appendix, the reason behind the scoring of table 21 and table 22 is presented.

Supplier reliance

Supplier reliance is unrated in both scenario 1 and scenario 2. Due to none of the alternatives affecting the resource requirement or production methods, the supplier reliance is equal across all alternatives. This makes for no performance differences, and thus it was opted not to include this in the rating scheme.

Risk

Scenario 1+2

Risk is evaluated equally for scenario 1+2. The best performing alternative is the nil-alternative, as it requires absolutely no change. Alternative 4 is the second best scoring means on risk, at is fully relies on already established principles that have proven to be effective. Alternative 2 is middle-class, as it requires investments in unproven electric trucks, however tests and previous experiments with electric cars have positive results. Using nylon as insulation material requires a new market to be established. With uncertainties in demand, supply, technology and the thermodynamic properties of nylon-6 as insulation material, alternative 3 provides big risks for the industry. Alternative 1 offers besides this newly created market also an option of waste incineration, of which yet no waste processing plant is capable of. It has two uncertain factors and thus scores last.

Supplier continuity

Again, unmarked, as supplier continuity is unaffected by all proposed alternatives.

Virgin resource reliance

Scenario 1 + Scenario 2

Virgin resource reliance is appraised equally for both alternatives. In the nil-alternative, 100% landfilling and long shipping distances cause it to score badly on the virgin resource reliance scale. Slightly better performing is alternative 2, which downcycles some EOL product and eliminates the need for diesel fuel, which is deemed to be compensated by the resource requirement of rare-earth metals in the construction of these zero-emission vehicles. Alternative 4 is rated in the middle: local collection reduces the shipping distance (oil reliance) and FRC downcycling offers a reduced requirement of virgin resources for the concrete industry. The two best performing alternatives, 1 and 3, both use downcycled nylon fibers for insulation purposes. This way, the nylon remains recyclable. Alternative 1 also reduces the waste production, thus achieving the optimal score on the virgin resource reliance scale.

Growth

Scenario 1

Growth in scenario 1 is primarily based on the financial costs of implementation. Alternative 2 is the worst performing measure as ZE-transportation means offer both a financial and physical obstruction to growth. Not only is the investment of ZE-transportation one with a slow pay-off, the range of ZE-trucks is limited as well. Alternative 4 offers little room for growth as well, as FRC is a cheap product and the willingness to pay and price for nylon fibers is estimated to be extremely low. Although growth in the nil-alternative might be bounded by environmental regulation in the near future, not investing in any alternative frees up funds for other, non-sustainable growth projects. Alternative 3 offers the establishment of a new market in which the carpet industry can have an invested interest. Regardless of the high risk and investment costs, alternative 1 combines three industries into one, combining carpet manufacturing, insulation and waste incineration. Thus, this is the best performing alternative.

Scenario 2

In scenario 2, alternative 2 remains the least favorable alternative, alternative 1 is the most desirable alternative, and alternative 3 is equally the second best performing alternative. However alternative 4 and the nil-alternative are reversed in score. This is due to the fact that in this scenario the establishment of new market/business opportunities comes free of charge. Thus, not attempting any expansion method at zero cost is deemed to limit growth.

RoI

Scenario 1

In scenario 1, the best performing alternative is alternative 4. With quick and easy gains at a low cost, this yields the best return on investment. The nil-alternative is the second best performing alternative, as all other alternatives require much capital with a return on investment period exceeding the 10 year boundary of the system. Alternative 2 is middle-class, as zero-emission vehicles can be leased and thus gradually accepted into the field. These however yield little gains. Investing in recycling machinery for decentralized collection is a very costly process, making alternative 3 score low on RoI. Alternative 1 requires a complete waste incineration process to be built with energy reclamation besides equipping all cities/municipalities with recycling machinery, making it the lowest scoring alternative.

Scenario 2

When the carpet industry is not responsible for any costs of sustainability increasing measures, a change can be observed compared to scenario 1. When the government pays for the creation of new waste incineration plants, alternative 1 gains two revenue models: EOL fibers as well as EOL incineration material. This makes alternative 1 score the highest. Alternative 3 features this newly created insulation market as well, where the nylon fibers are more valuable than for FRC, making it score the second best. Alternative 2 remains the middle alternative, as zero-emission trucks are estimated to have reduced operating costs. Alternative 4 offers the least amount of RoI besides the nil-alternative, as it does not explore any new markets or revenue models other than the creation of FRC, a relatively cheap product.

Purchase price of a unit carpet tile

Scenario 1 + Scenario 2

The scores on the purchase price are the product of required capital to implement the alternative. The cheaper the alternative in the first scenario, the better an alternative scores. For scenario 2, the purchase price is reduced for all scenarios, as new gains are achieved. As discussed earlier, alternative 1 offers two additional revenue models, alternative 3 offers one new revenue model, alternative 2 is eventually able to reduce cost due to decreased transportation costs, and finally alternative 4 offers a little reduction in costs due to decreased transportation distances.

Landfill potential

Scenario 1 + Scenario 2

In both scenarios the landfill potential is equal. The nil-alternative features a 100% landfill potential of a carpet tile, offering at best 1.1525 grams of material per carpet tile to be landfilled. FRC is constructed using 2% nylon fibers and cannot be recycled at its EOL. One carpet tile can then produce 0.8 kg of landfilled backing material plus 17 kg of landfilled FRC. Alternative 1 offers incineration, which completely eliminates the need for landfilling, and alternative 3 effectively and sustainably recycles nylon fibers, making it the second best performing measure.

Tonkilometer (Shipping of product per weight per distance)

Scenario 1 + Scenario 2

In both scenarios, the travel distance is equal. With no reduction in shipping distance and an increased weight of the vehicle itself, the total mileage and transported weight of alternative 2 is the worst-performing of all alternatives, followed by the nil alternative. Alternative 4 offers local collection, which is a great reduction in tonkilometers, however still assumes that the separated Nylon 6 fibers are shipped to one of the few FRC manufacturers in the Netherlands. Alternative 3 supplies these Nylon 6 fibers to local insulation companies, thus further reducing the total shipping distance. Alternative 1 is the best performing alternative due to the local collection and zero-waste manufacturing, which is the only alternative that limits the shipping distance and total transported weight.

Reverse logistics

Identified through the annual report of Desso, none of the alternatives offer any kind of reverse logistics back to the manufacturer. The necessity of this RL stream is disputed by this research, as a decentralized approach to the logistics is deemed more beneficial. Thus, RL is not included in the calculation of the scores.

Green image

Scenario 1 + Scenario 2

Currently, no recycling efforts are made by the industry. On the green image, the nil-alternative scores the lowest. Using EOL product to insulate homes, allowing for further energy savings, emits a very positive image. Alternative 1 requires the construction of an incineration plant, which could impact this perception of sustainability by the consumer/client. The creation of FRC is however less environmentally desirable, as FRC is not recyclable. Alternative two compensates a little for this effect by using zero-emission vehicles for transportation, but alternative 4 will score just above the nil-alternative.

Quality

Scenario 1 + Scenario 2

Alternative 1 changes the production method of carpet tiles to facilitate a zero-waste production method. This might cause some decreases in carpet quality, as for instance edges are left untrimmed. This is however uncertain and as such does not receive a negative rating. However, all other alternatives have an unaltered production method and thus score optimal on the quality.

Costs of implementation

Scenario 1 + Scenario 2

Regardless of who carries these costs, some alternatives are cheaper to implement than others. Within the nil-alternative, no investments are required. Thus, this is the best alternative, followed by alternative 4 which relies on already established institutions and products. Alternative 3 requires some investigation into implementation of Nylon as insulation material and carpet recycling equipment, thus making it score average. Alternative two requires the investment of a new fleet of trucks, which is deemed more costly than some shredding machines with an integrated compressor. Finally, the purchasing of new manufacturing equipment to facilitate zero-waste production, combined with the construction of new waste incineration plants, is deemed to be, by far, the most expensive alternative.

Speed of implementation

Scenario 1 + Scenario 2

The costs of implementation also give a measure of complexity. Local collection with recycling as well as ZE-transportation measures can be implemented gradually and do not require a full coverage straight away.