The case of Re-plex: Wastewater to building material

Life Cycle Assessment on the use of Re-plex as an interior finishing material

Master Thesis for Industrial Ecology

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Foreword

The last half year that I have been working on this master thesis have been quite intense working from home. From online meeting to online meeting. Nonetheless I have had a great experience that has taught me useful skills in working individually for a future career. I hope that the LCA study on Re-plex will be used to improve the environmental performance of this new material. I hope you will have an insightful experience reading my Industrial Ecology master thesis.

I want to thank Mark van Loosdrecht for being my supervisor and Lauran van Oers for being my second supervisor. They have been of great help in our bi-weekly meetings. My sincere thanks to all the people that have helped me on the way, I could not have produced the work I have now without your help. Primarily Philipp Kehrein and Philipp Wilfert have helped me a lot with data validation and getting me on the right track. It was nice to meet Philipp Kehrein in person the one day that I was on the TU Delft campus.

Thanks to the COMPRO team for supporting me and helping me obtain data on the Re-plex production. Specially Peter Mooij, Jure Zlopasa and Mark Lepelaar have been of great help. I will remember the jokes Jure made to make the online meetings more lively. Other COMPRO members that have helped me along the way are Stephen Picken, Nicole Poort, Ian Jansen, Willem Bottger, Zoya Zarafshani and Robbert Binnenveld. Thank you for discussing assumptions and providing new insights to me.

Abstract

With the increasing focus from policymakers to a circular economy, assessing the environmental impacts of circular products is becoming more important. In this thesis a Life Cycle Assessment of the new circular composite Re-plex is performed. The Re-plex can be used as building material. Re-plex is produced from Kaumera Nereda® Gum recovered from Nereda® wastewater sludge, and Recell® cellulose recovered from wastewater. Re-plex is still in the developmental phase, this LCA is performed to aid engineers to reduce the environmental impacts of the Re-plex composite. A comparative LCA is performed in which the current Re-plex production is compared to Fire-retardant Medium Density Fibreboard (FR-MDF) with the ILCD impact assessment family. The functional unit is 1 year of 1m2 use of interior finishing material.

The Re-plex has a better characterisation result in the impact category; Human Health (HH), respiratory effects, inorganics. The FR-MDF has better characterisation results in the impact categories; Climate change; Ecosystem Quality (EQ), acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ ionizing radiation; EQ, marine eutrophication; EQ, marine eutrophication; Human Health (HH), carcinogenic effects; HH, ionizing radiation; HH, non-carcinogenic effects; HH, ozone layer depletion; HH, photochemical ozone creation; Resources (RS), land use; and RS, mineral, fossils and renewables.

Scenarios are developed to improve the environmental performance of the Re-plex production. Increasing the amount of cellulose in Re-plex does not seem to improve the environmental performance. Three scenarios do improve the environmental performance; Replacing citric acid by succinic acid; improving the energy efficiency; and drying the Kaumera Gum before transport. These three improvements are combined in the new Re-plex scenario. The improved scenario has better characterisation results than FR-MDF in the ten impact categories; Climate change; EQ, acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ, marine eutrophication; EQ, marine eutrophication; HH, carcinogenic effects; HH, non-carcinogenic effects; HH, photochemical ozone creation; and HH, respiratory effects, inorganics. FR-MDF scores better in the five impact categories; EQ ionizing radiation; HH, ionizing radiation; HH, ozone layer depletion; RS, land use; and RS, mineral, fossils and renewables.

Engineers working on Re-plex are advised to change the use of citric acid to a better environmentally performing material. The environmental benefit of changing this material will add more value to a Re-plex product than the lower price when using citric acid. Further, the focus should be on improving the energy efficiency of Re-plex production and realising a lifetime of Re-plex of 32 years, similar to MDF. If these improvements can be realised, Re-plex has a better environmental performance than FR-MDF.

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1. Introduction

Wastewater has traditionally been seen as a burden. The costs of wastewater treatment in Europe are approximately €46 for water use per person per year (Bode & Lemmel, 2001). The main function of wastewater treatment is the removal of pathogens and chemicals to protect public health. Next to this, the removal of carbon, nitrogen and phosphorus compounds is an important function as these compound pose a serious eutrophication treat to surface waters (Chislock, Doster, Zitomer, & Wilson, 2013). However, these compounds are also valuable and can be used for energy recovery or as fertilizer. This poses an opportunity for recycling from wastewater. Recycling serves a dual purpose: First, reducing environmental impact by reusing a waste stream, contributing to a circular economy. Second, providing additional revenue for wastewater treatment plants, reducing wastewater treatment costs.

The opportunities of nutrient recycling are also recognized by the European commission, who funds the research project Water Mining (Communication TNW, 2020). This project is led by the TU Delft, and includes Universities, wastewater treatment industry, governmental bodies and societal actors. The aim of the Water Mining project is to test and scale up new recycling technologies in Europe and research the societal values for implementation of these technologies (Waterming.eu, n.d.).

One of these promising technologies for wastewater recycling is the Nereda® technology, a granular sludge wastewater treatment technology (RoyalHaskoningDHV, n.d.)). After wastewater treatment a bio-polymer can be recovered from the sludge granule material. The bio-polymer can be processed into a product called Kaumera Nereda® Gum (Kaumera, n.d.). Kaumera is a product that has unique material properties. It can be used as a bio-stimulant, used in agriculture to improve plant metabolism, and is successfully used as a biodegradable coating for artificial fertilizer. A product of Kaumera as bio-stimulant and slow-release coating for fertilizers is produced in a pilot plant for commercial application (van de Knaap et al., 2019). Next to this first application, other unique material properties are that Kaumera binds very well to other materials and is fire retardant. This poses opportunities for the use of Kaumera as material in composites. The main circularity benefit of this application lies in the biodegradability of the Kaumera gum, making it possible to compost the composite material. A Kaumera and cellulose fibre composite can be used as an interior building material. This composite is currently being developed under the name Re-plex. The application of Kaumera in the Re-plex composite material is the focus of this paper.

The development and application of Kaumera is interesting for Industrial Ecology from three perspectives. From a technological perspective Re-plex has a lot to offer. The operation conditions of the Nereda® wastewater treatment plant and the extraction procedure of Kaumera from wastewater sludge both influence the properties of the Kaumera bio-polymer. In this regard still a lot of optimization of the Kaumera Nereda® gum properties can be realised. In addition to this the formulation of a composite has a large influence on the material properties of the Re-plex composite. The formulation can be optimised based on the specific application of Re-plex.

Next to technical process optimization, the environmental performance and social acceptance of the Re-plex composite are of importance. From an environmental point of view, it is important to assess to what extent the extraction of the Kaumera bio-polymer from wastewater sludge is able to reduce the impact of wastewater treatment by reducing the amount of wastewater sludge to be handled. And to what extent Re-plex will have a better environmental performance compared to the products it replaces. The focus of this thesis will be on the latter question, but the importance of a holistic view should be stressed. This includes taking all life cycle impacts (e.g. global warming, human toxicity, eutrophication, ozone depletion) into account.

From a social and end-user point of view, the relevance of the social implications of the technology should not be underestimated. For society, the costs of water treatment are an important consideration when resource recovery technologies are applied, while limited user acceptance due to smell or a dirty image of products recycled from wastewater can be a bottleneck for successful implementation. A third obstruction can be regulation regarding waste treatment and product recovery. Regulations can prohibit the use of products with a waste-status for certain applications.

The application of the composite material Re-plex is the focus of this thesis. This new material that can have a wide range of possible applications, depending on the formulation and filler materials used in the composite material. The production of Re-plex is still in the developmental stage, no pilot plant is operating yet. In association with COMPRO, a research project working on the development of Re-plex, this thesis will assess the environmental performance of Re-plex compared to a conventional composite material from a life cycle perspective.

Important to note is that, while the Re-plex might perform worse than the composite material that it is compared with, the wastewater sludge treatment can still perform better with Kaumera extraction than for direct sludge treatment. Visser et al. (2016) found that the impacts of Nereda® wastewater sludge treatment were lower with Kaumera extraction. They assumed substitution of alginate by Kaumera (aliginate is used as a biostimulant). If the Re-plex has higher impacts than conventional composites, other applications of Re-plex or Kaumera should be investigated. This thesis will not be able to answer the question if the total system of Nereda® wastewater sludge treatment and Re-plex use will have a better environmental performance than standard Nereda® wastewater sludge treatment. It will be able to answer the question if Re-plex performs environmentally better than conventional composite materials.

Standard composite materials such as Medium-Density Fibreboard (MDF) or High Pressure Laminate (HPL) are unfavourable as a building material due to their (partly) oil-derived origin and harsh chemicals used. Further the inseparability at the end-of-life is unfavourable for recycling, leaving incineration as only recovery option. The goal of COMPRO is to develop a bio-based and circular Re-plex product, derived from a waste stream, thereby contributing to a circular economy. It should be biodegradable, such that the composite can be either recycled, digested in a composter or left in the ground for natural degradation.

The Re-plex is produced by adding cellulose fibres to the Kaumera gel. These cellulose fibres are currently recycled fibres from wastewater treatment plants called Recell® (Recell, n.d.). Further biobased additives are added to obtain more favourable material properties. This formulation is however still in the developmental phase and can still be changed in order to obtain other material properties. The environmental comparison of Re-plex with other composite materials will be done by performing a Life Cycle Assessment (LCA). The main goal of this thesis is to aid engineers in the development of a Re-plex composite that is able to replace a conventional composite material while having a better environmental performance. It will give targets for improvement of the environmental performance of Re-plex. Further the paper is aimed at policy makers to help them assess the environmental performance of a Re-plex composite. This should help policymakers in decision making on stimulating policies for a Re-plex composite product.

First a literature review regarding the state of the art in wastewater treatment is discussed. Based on the literature review knowledge gaps will be identified, resulting in a research objective and main research question. A research approach is described and sub-questions are proposed, which can lead to answering the main research question. Further the research methods will be presented, describing data collection and the tools used to answer the research questions.

1.1 Literature review & Knowledge gap

1.1.1 Literature review

For different regions in the world, different constituents in municipal wastewater pose opportunities for recycling. Especially in dry regions where water scarcity plays a role, the production of potable water from wastewater is a great opportunity. Water recycling can be easily implemented in wastewater treatment, although it requires a significant amount of energy (Pasqualino, Meneses, & Castells, 2011) and raises concerns regarding user acceptance ('Battling Water Scarcity', 2013; Browning-Aiken, Ormerod, & Scott, 2011; Burgess, Meeker, Minton, & O'Donohue, 2015; Kehrein et al., 2020).

Energy recovery using anaerobic digestion is an opportunity to decrease the use of fossil fuels in wastewater treatment. For energy recovery anaerobic digestion of the organic fraction in the wastewater can be employed. This process produces methane from the hydrocarbons in the water (Rosso & Stenstrom, 2008) and can produce the total energy demand of a wastewater treatment plant (Bertanza, Canato, & Laera, 2018; Kehrein et al., 2020). This is often implemented in the standard operating condition in Dutch wastewater treatment plants (Visser et al., 2016).

The recycling of nitrogen- and phosphorus compounds poses a great opportunity for fertilizer production. Phosphorus mines are depleting and phosphorus is expected to become a scarce resource (Neset & Cordell, 2012). Nutrient recycling can be done by direct land application of the sewage sludge. Sewage sludge land application compared to landfill has a lower abiotic depletion potential and global warming potential, due to the avoided artificial fertilizer production. However, land application has a higher ecotoxicity and eutrophication potential, due to the heavy metal and nitrogen emissions from the sludge (Lombardi, Nocita, Bettazzi, Fibbi, & Carnevale, 2017). Alternatively, the nitrogen and phosphorus can be recovered during the treatment process. Struvite, a compound consisting of nitrogen, magnesium and phosphorus, can be recovered for nitrogen and phosphorus recycling. A second strategy is removing the phosphorus from the fly-ash obtained after incineration of wastewater sludge (Visser et al., 2016).

Lastly, chemical production from the organic fraction in wastewater poses great opportunities. Chemical products can be obtained from fermentation of the wastewater broth. Products that can readily be produced in this way are Volatile Fatty Acids (VFAs) or Polyhydroxyalkanoate (PHA). A novel

Water Reuse	+ Water scarcity
	+ High population density (large volumes of wastewater generated)
	+ Government subsidies
	- Proximity to the coast (access to seawater for desalination)
	- Lack of knowledge about the safety of reclaimed water
	- Lack of regulations for water reuse
Energy Recovery	+ Higher energy costs
	+ High relative proportion of fossil fuels used
	+ Regulations limiting emissions
	+ High landfill costs
	+ Government subsidies
	- Electricity mix with a low emissions factor
Nutrient Recovery	+ Close proximity to point of reuse (e.g., agricultural lands for land application)
	+ Prevalence of farming
	+ High landfill costs
	+ Government subsidies
	- Regulations restricting land application of biosolids
	- Urban environments where farmlands are located far away

Figure 1: Local factors promoting (+) or hindering (-) implementation of wastewater recycling regarding water reuse, energy recovery and nutrient recovery. Reprinted from Diaz-Elsayed et al. (2020).

product category to be recovered are Extracellular Polymers (EPS), of which Kaumera is an example (Kehrein et al., 2020).

An overview of promoting or hindering factors for wastewater recycling is given in figure 1. A comprehensive overview of all currently available recycling methods for water reclamation, energy recovery, nutrient recovery and chemicals production is given in Kehrein et al. (2020). Corominas et al. (2013) discuss 40 LCA studies of wastewater treatment plants and describe the paradigm shift from wastewater treatment to resource recovery as difficult. The Dutch waterboards see resource recovery from wastewater as an opportunity for Dutch wastewater treatment plants. The NGO for scientific research into water management (STOWA) does research on recycling technologies for the waterboards. The direct application of wastewater sludge on agricultural land is prohibited in the Netherlands, contrary to other European countries such as Portugal and Spain. This makes the sludge treatment a compulsory step in the wastewater treatment business. Therefore recycling options pose a greater potential in the Netherlands than in less developed countries.

The STOWA published a report on an LCA of recycling technologies compared to conventional wastewater treatment from a wastewater treatment perspective (Visser et al., 2016). They studied how the recovery of materials from wastewater would reduce the impacts of wastewater treatment. For the recovered products they used substitution with conventional products to solve multifunctionality of the product system. With this method the impacts of the conventional products are subtracted from the impacts of wastewater treatment, therefore their results are based on the product that is claimed to be replaced. They studied phosphorus(P)- and chemicals recovery compared to a baseline treatment process with anaerobic fermentation in which only biogas is produced. As this is the standard for wastewater sludge treatment in the Netherlands. P-recovery from wastewater is possible either by removal from the sludge incineration fly-ash or by struvite recovery. P-recovery from fly-ash is already happening on pilot scale, in which the recovered P is sold by the company Ecophos. This results in 82% P-recovery from the wastewater sludge. P-recovery in struvite reactor with a wash-strip results in 47% P-recovery from the wastewater sludge. Struvite can readily be used as a fertilizer. According to the LCA by Visser et al. (2016) both methods result in lower environmental impact for the wastewater treatment than the baseline. Struvite recovery has the lowest environmental impacts due to avoided emissions of artificial fertilizer production, while fly-ash P-recovery only avoids phosphate-mining.

For product recovery Visser et al. (2016) studied impacts associated with PHA production, cellulose recovery and bio-polymer (Kaumera) production. PHA production results in significantly lower aggregated environmental impact for the wastewater treatment function than the baseline. However, uncertainty in the data is large, which could result in no improvement in environmental impact for the wastewater treatment for a badly designed PHA production facility. Cellulose recovery can be used for energy by burning the obtained cellulose for electricity and heat generation, or to produce new fibre-material. Both routes result in lower environmental impacts for the wastewater treatment function compared to the baseline. Use of the recovered cellulose as fibre-material performs better than energy recovery since it avoids the use of virgin fibres, which results in higher avoided emissions in the wastewater treatment. However this application may be hampered due to a lack of social acceptance. Lastly, Kaumera production can be performed in Nereda® wastewater treatment systems. This technology obtained the best results out of all recycling technologies in terms of reducing the environmental impact of the wastewater treatment function due to the avoidance of the high environmental emissions of alginate-production.

The main conclusions are that the recovery of a product from sludge fermentation and P-recovery can and should ideally be combined in one WWTP. The remaining organic fraction after fermentation can and should still be further anaerobically digested to biogas. This would result in the lowest environmental impact for a wastewater treatment plant.

1.1.2 Knowlegde gap

The STOWA report by (Visser et al., 2016) on recycling technologies in wastewater treatment plants in the Netherlands gives a good overview of the environmental impact of resource recovery from municipal wastewater from a wastewater treatment perspective. This model can be used to serve as a basis to expand an LCA model specifically for Re-plex. According to van de Knaap et al., (2019) the LCA model needs to be updated since the extraction of Kaumera can be performed by different extraction methods based on the application. Furthermore, the model is does not study the avoided emissions of Kaumera end-products compared to conventional products, it uses substitution of alginate by Kaumera. The substitution of other end-products has not been studied due to the wide variety of applications Kaumera can have. The need of LCAs on Kaumera from a product perspective is stressed by van de Knaap et al. (2019), they performed a preliminary environmental impact analysis of using the Kaumera in different products. However, this analysis was limited to the application of Kaumera in the fertilizer industry. An LCA on Kaumera for its variety of applications has not yet been performed. The application of Kaumera in composite material Re-plex is still in development. Therefore this is the optimal moment to perform an environmental impact analysis. The results from the LCA can contribute to the development of a Re-plex formulation with low environmental impacts. This can be done by performing an ex-ante LCA. This kind of LCA models a technology in developmental phase based on scenario planning of the technology projected as final system. The use of scenario planning in an ex-ante LCA can help engineers in their search for environmentally optimal Kaumera composite production processes (Cucurachi, van der Giesen, & Guinée, 2018).

2. Research approach

From the literature review it is clear that there is need of a better comparison of Re-plex from a product perspective. This is done with an ex-ante LCA, in which scenario planning is used to obtain an accurate representation of the environmental impacts of Re-plex. This results in the research question:

What is the environmental performance of the Re-plex material compared to conventional composites and how can the environmental performance of Re-plex be improved?

The research approach makes use of quantitative modelling. An LCA model of the Nereda® sludge treatment process and Re-plex production is made. This model is used to compare the environmental impacts to a conventional composite product in the context of the Netherlands. The research approach starts with data collection of Dutch wastewater treatment practices and obtaining inventory data on extraction of Kaumera from sludge. Data on the production, use and end-of-life of Re-plex is gathered by using expert interviews. Since the application of Re-plex is not yet commercially available the data will have some uncertainty issues, these are resolved as much as possible by using data from pilot studies, expert judgement and a sensitivity analysis. Next to this data on the production, use and end-of-life of conventional composite materials that can be replaced by Re-plex is gathered using desk research. This approach results in following sub-questions:

- What are conventional composite materials and how does their production, use and end-of-life take place?
- How does the production, use and disposal of Re-plex take place?
- What are the contributions of the processes used for Re-plex production and use to the environmental impacts?
- How can the Re-plex production process be improved to reduce the environmental impacts?

The data collection, methods and tools to answer each sub-question are discussed below. A research flow diagram is added to summarize the research methods (Figure 2).

Data collection starts with obtaining data on wastewater treatment from the STOWA report (Visser et al., 2016). This is a solid basis to expand the LCA model on. The extraction of Kaumera from Nereda® wastewater sludge is modelled by Visser et al. (2016). Since this model is created in 2016, the extraction method used in this model can differ from updated Kaumera extraction. The model is reviewed and updated to reflect the current operational methods. The next step is using expert interviews to obtain data on material properties of Re-plex. Furthermore, the formulation and fabrication of Re-plex from Kaumera and cellulose is obtained. Recell® did not want to provide data on the cellulose production process. Instead data on the production of cellulose from waste paper is used. From the expert interviews an LCA model is developed on the production, use and end-of-life of Re-plex material. This model is reviewed by said experts. To obtain an alternative material that Re-plex is able to replace, selection criteria are developed. These criteria are quantified in a pugh matrix and a conventional building material is selected to compare Re-plex to. A literature study on this conventional building material is performed to make a model for the production, use and end-of-life stage for the conventional composite.

For a quantitative comparison an ex ante Life Cycle Assessment (LCA) is performed. The Nereda® sludge Kaumera extraction process and use of Kaumera in composite material is modelled in CMLCA software and assessed using the European ILCD impact assessment family (European Commission, Joint Research Centre, & Institute for Environment and Sustainability, 2011). CMLCA software (CMLCA Version 6.1; Heijungs, 2018) is used because it has many options to manually adjust methods (e.g. allocation methods, impact assessment families) compared to software such as Simapro (‘SimaPro | The World’s Leading LCA Software’, n.d.). Next to this, CMLCA software is free and open source, making the model easily accessible. The ILCD impact assessment family is the European Commission’s standard for LCA. Since this paper is related to the EU sponsored water mining project, this is the preferred impact assessment family. Further, this aides the ability to compare this LCA to other LCAs on a European level. The Dutch standard used by the National Institute for Public Health and the Environment (RIVM) and the STOWA is the ReCiPe impact family. Therefore this impact family is used in the sensitivity analysis.

An LCA can be used to determine the whole life-cycle impact of the wastewater treatment and use of Re-plex, and although the result is influenced by uncertainty issues this is minimized as much as possible. The LCA is used to determine hotspots in impacts. This can aid engineers in developing a Re-plex product with low environmental impact and policymakers in promoting the use of a Re-plex product with low environmental impact. This LCA results in quantitative recommendations for the use of the Re-plex composite materials from an environmental point of view

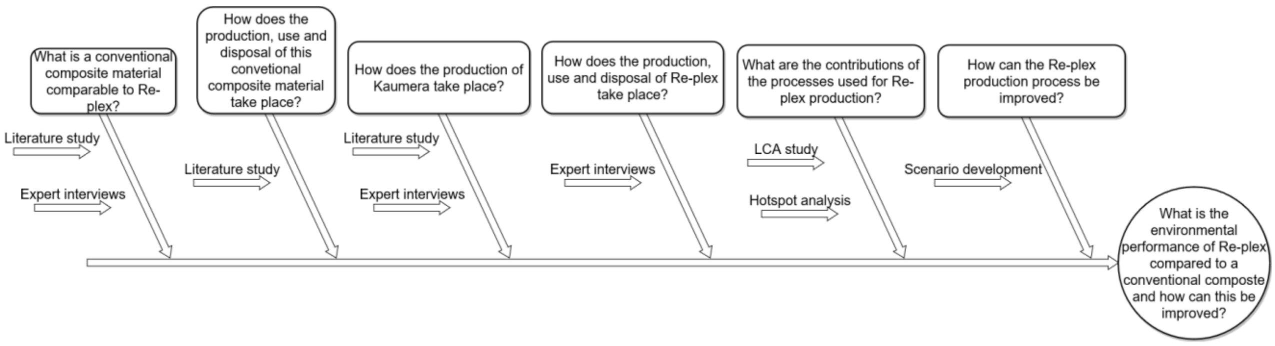


Figure 2: Research flow diagram. A summary of the data collection and analysis to answer the three sub-questions. The results for the sub-questions will result in the construction of an LCA model, which will be used to answer the main research question.

3. Selection of alternatives

For the LCA study, the Re-plex material is compared to alternative materials providing the same function. To obtain reasonable alternatives, the specific properties of the Re-plex material are compared to conventional composite materials. First the selection criteria for comparison between materials will be discussed. Second the conventional composites will be discussed. Last the quantification of the criteria and a final selection of alternatives for the LCA study will be discussed.

3.1.1 Selection criteria

The selection criteria have been devised with the help of experts from the COMPRO project: Peter van Mooij from the Amsterdam Metropolitan Solutions (AMS), Steven Picken and Jure Zloposa from the TU Delft material engineering department and Mark Lepelaar from NPSP. The selection criteria aim to quantify 3 properties: data availability on the material, material properties and market potential. An overview of the selection criteria is given in table 1.

As an indicator for data availability, it is determined if the material production process is present in the Ecoinvent 3.4 database. This eases comparison between the materials since the alternative material production process does not need to be modelled manually.

As indicators for the material properties the position in an Ashby plot and for building materials the flammability of the material are indicators. An Ashby plot has two material properties plotted against each other: the tensile strength (stretching strength) and the Young's modulus (bending strength). These two properties give a general understanding of the interchangeability and possible applications of materials. Next to this the flammability of the material is an indicator. Since Re-plex is naturally a great fire-retardant, it would be suitable to replace a flammable building material which needs a flame retardant coating to be applied. Flame retardant coatings have high toxic emissions and are a target for replacement.

As indicator for market potential the market price of the composite is used. Since the production cost of Re-plex at the current scale needs to be competitive, the goal is to replace a higher value product with Re-plex.

3.1.2 Conventional composites

The conventional composites that the Re-plex can reasonably replace at its current technology stage are described here. These conventional composites have been devised based on the expert intuition of the experts from the COMPRO project: Peter van Mooij, Steven Picken, Mark Lepelaar and Jure Zloposa. Next to this, the position in the Ashby plot has been used to obtain potentially replaceable materials. This resulted in a list of seven materials in table 1. Three of them are building materials: Medium Density Fiberplate, High Pressure Laminate and Gypsum board. Four composites could be replaced for other applications: Glass-fibre, Aluminium, Poly-Lactic Acid and Polypropene.

Table 1: Pugh matrix for comparison of materials that can potentially be replaced by Re-plex. A green score indicates a plus result, an orange score indicates a neutral result, a red score indicates a minus result. For the 3 building materials MDF, HPL and Gypsum board the total score is indicated.

Criteria for alternative materials	Re-plex	MDF plate	HPL plate	Gypsum board	Glass-fibre	Aluminium traffic sign	PLA coating	Polypropene item
Data availability on composite (Ecoinvent 3.4)		Yes	No	Yes	Yes	Yes	Yes	Yes
Tensile strength (MPa)	7-8	28-80	36	1.5-2.4	2000	100-600	47	20-50
Youngs modulus (GPa)	4	2-5	20-24	1.7	100	70-90	0.06	1-2
Flamability (European fire rating)		D-E	D	B				
Market price composite (made-in-china.com)		2-20/m2	10-80/m2	0.69-0.8/m2	1-20/kg	1.15-1.35$/kg	2.7$/kg	2-2.5/kg
Total score		3	1	1				

3.1.3 Selection of alternative composites

The focus of the LCA study will be on a building material that is able to be replaced by Re-plex. Therefore the choice of an alternative material is between MDF, HPL and Gypsum board. The other four materials that Re-plex could replace are not building materials. MDF and Gypsum board are in the Ecoinvent 3.4 database, while HPL is not. The Youngs modulus of MDF and Gypsum board is lower than Re-plex', making Re-plex a structurally suitable replacement. HPL has about double the value for Tensile strength and four to five times the value for Youngs modulus. Therefore the application of Re-plex as HPL replacement is not favourable. Regarding the flammability of the materials MDF performs the worst with a European fire rating of D to E, HPL plate has a rating D and gypsum board has a rating of B. Since Re-plex is a natural fire retardant it is best to replace a building material which needs to have a fire retardant coating applied. This would be the case for MDF and HPL, while gypsum board is also a natural fire retardant. The market price of HPL is high at $10-80$/m2, compared to MDF at $2-20$/m2 and the low value gypsum board at $0.69-$0.8/m2. In the pugh matrix (table 1), a green tile indicates a relative good result, an orange tile indicates a relative average result and a red tile indicates a relative bad result. Based on the values in the pugh matrix result MDF yields a score of 3, and HPL plate and gypsum board both score 1. Based on this Pugh matrix the MDF plate was considered the most suitable product to be replaced by Re-plex.

4. Life Cycle Assessment of Re-plex

4.1 Goal and scope definition

4.1.1 Goal

The goal of this LCA study is to determine the environmental impacts of the use of Re-plex material compared to conventional use of a composite material (Medium Density Fibreboard). The production for Re-plex is still in development, thus scenario planning is used to estimate efficiencies for a market scale production processes. The LCA is aimed to enhance the knowledge of the environmental impacts of Re-plex to aid engineers in developing a product with a low environmental impact. A hotspot analysis is performed to elucidate the main contributors to the environmental impacts. This can guide engineers in improving the environmental performance of the final Re-plex product. Further, the LCA can be used to aid policymakers in decision making for increasing the use of circular building materials. To this aim the ILCD European impact assessment family is used, this method uses 15 midpoint impact categories; Climate change; Ecosystem Quality (EQ), acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ ionizing radiation; EQ, marine eutrophication; EQ, marine eutrophication; Human Health (HH), carcinogenic effects; HH, ionizing radiation; HH, non-carcinogenic effects; HH, ozone layer depletion; HH, photochemical ozone creation; HH, respiratory effects, inorganics; Resources (RS), land use; and RS, mineral, fossils and renewables (European Commission et al., 2011). This impact assessment family is used to ease comparison between LCAs for policymakers on both a national and European level.

There is no scientific consensus on the use of a single score indicator (Pizzol et al., 2017). Still, a single score model is used to aid policymakers in a choice between FR-MDF or Re-plex. The Milieu-Kosten Indicator (MKI) single score model, which is standard in the Dutch building sector, is used (Stichting Nationale MilieuDatabase, 2020).

The LCA is commissioned by Mark van Loosdrecht and Lauran van Oers from the Technical University Delft and Leiden university as part of a Master thesis project. Primary data collection has been performed in collaboration with the COMPRO project developing a Re-plex product. COMPRO consist of public actors such as TU Delft and the Amsterdam Metropolitan Institute (AMS), but also private companies such as NPSP and Chaincraft. This thesis is disclosed to the public for 2 years to protect intellectual property (until 8 July 2023). A non-disclosure agreement has been signed by both parties for information obtained from COMPRO on the production of Re-plex.

4.1.2 Scope

The scope of the LCA study is an analysis of the whole lifecycle of Re-plex, a cradle to grave perspective is used. This includes the treatment of wastewater sludge from which Kaumera is extracted, the production of the Re-plex finishing material for interiors from Kaumera, the use of the material, and the end-of-life treatment of the material. Further, attributional LCA will be used. The market dynamics of changing consumer behaviour thanks to the introduction of Re-plex is out of scope for the study. Due to the limited scale of current Re-plex production, an ex-ante LCA will be used as described by Cucurachi, van der Giesen, & Guinée (2018). This entails the development of different scenarios for the efficiency of a Re-plex production process at market introduction. The production process for conventional composites is modelled with current technology level. The geological scope will be limited to the Netherlands since the Kaumera production facilities are located in the Netherlands. The LCA study resulted in a report with an inventory analysis, the ILCD midpoint impact assessment and a stage contribution analysis. Further, scenarios for improvements to Re-plex production are developed. The impact assessment is performed for both the current technology level of Re-plex, and for scenarios with improved efficiencies and improved chemical use. This will result in recommendations for engineers in developing a less impactful Re-plex product. The LCA will be reviewed by both engineers and researchers working on Re-plex from the TU Delft and the COMPRO team. Further it is reviewed by the LCA expert Lauran van Oers from Leiden University.

4.1.3 Function, functional unit and alternatives

This LCA will focus on the application of Re-plex as a finishing material for interiors. Since Re-plex is fire-retardant, the function in this LCA is the use of a fire-retardant finishing material for interiors. The functional unit needs to account for the amount of finishing material used, therefore a surface and time dependant functional unit is chosen. The surface determines the amount of material used, and if a material has a shorter lifetime, this results in less years that the material is able to fulfil its function. Further the definition of fire-retardant from the European Union is used, with a fire rating of A1, A2 or B being considered fire-retardant material.

The functional unit used in this LCA is 1 year of 1 m2 of fire-retardant plate finishing material for interiors use.

The alternatives are the use is 1 year use of 1 m2 of 8mm thickness Re-plex composite, which is fire retardant by nature. Or 1 year use of 1 m2 of 12mm thickness MDF composite with a fire-retardant coating.

4.2 Inventory analysis

4.2.1 System boundaries

The system boundaries are the boundaries between the environment and the economy, or the boundaries between different product systems. Such as the product system for wastewater sludge treatment, and the product system for Kaumera production. The setting of this boundary requires a solution for the multifunctionality of processes related to both product systems. These solutions will be discussed at the end of the inventory analysis. Environmental flows enter or leave the system boundary. Flows from the environment do not have prior transformations by humans, while flows within economy do have prior transformations by humans. Flows to the environment are emitted by economic processes, but have no further human transformations and end up in the environment. Some economic flows also leave the system boundary. The functional flows leave the system boundary since this is the output of the system. Co-products are also leaving the system boundary, since these are considered to be part of another product system. Further, cut-off processes are considered to be coming from outside the system boundaries since no economic process is modelled to produce the cut-off products.

Since Kaumera is a circular product, derived from wastewater treatment sludge, an LCA on Kaumera has to address allocation of multiple functions. Namely, wastewater sludge treatment and the use of Re-plex as interior finishing material, but also energy recovery from the wastewater sludge. All of these functions are performed during Kaumera production. The non-functional flows of the processes producing multiple functions are allocated over these functions. A detailed description of how multifunctionality is solved is described at the end of the inventory analysis (Multifunctionality & allocation). The product system used in this LCA is the production and use of the Re-plex composite material in buildings.

4.2.2 Cut-off

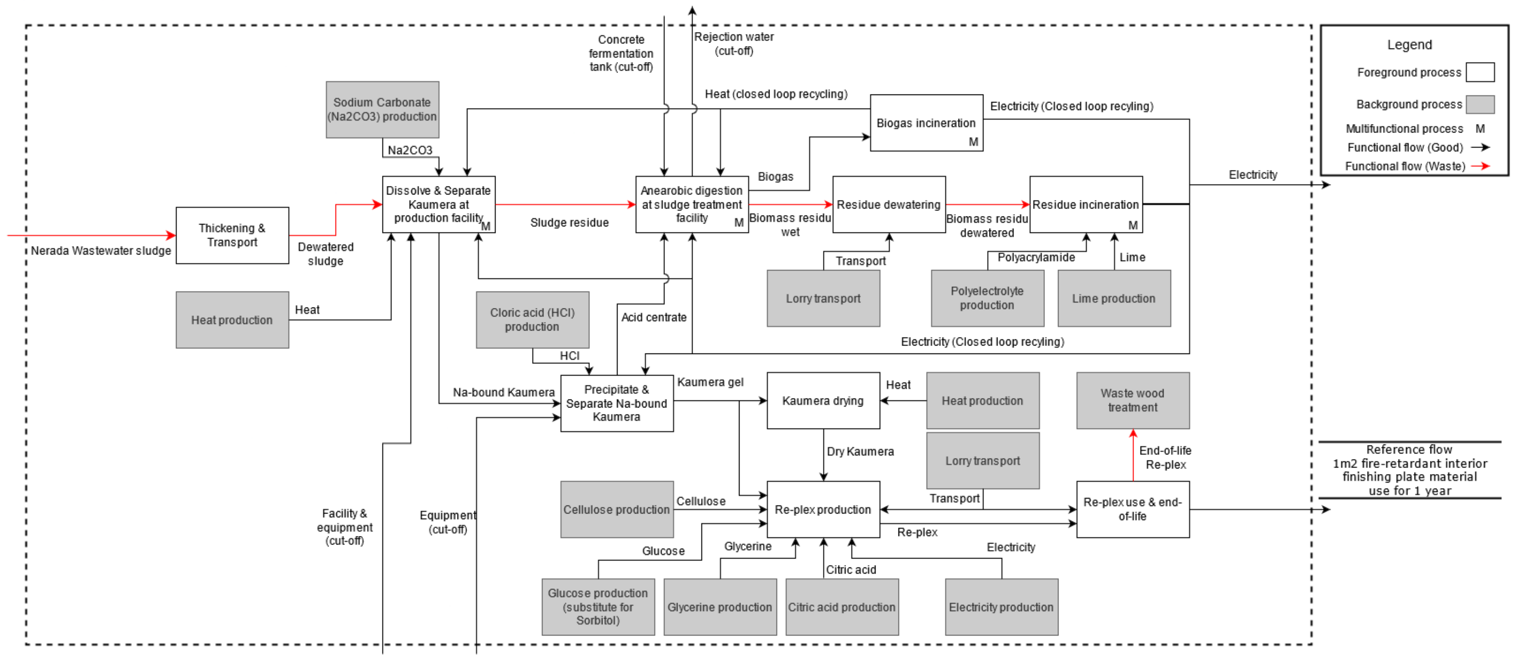
Cut-offs are economic flows that are not considered part of the product system because these are out of scope (see Goal & scope definition), or because of data constraints, time constraints or an expected negligible contribution to the emissions. The cut-offs in the Re-plex product system are discussed here.

The wastewater treatment is cut-off until the wastewater sludge inflow. This is considered part of the wastewater treatment product system, not of the Kaumera product system. Since the Nereda® wastewater treatment process is the same regardless of the extraction of Kaumera, all the impacts of wastewater treatment will be equal and these processes can be cut-off. Further the cut-off boundaries are at the level of raw materials. Capital goods such as buildings, concrete tanks and equipment are not included since these have a long lifetime and can be used for other purposes when the extraction process is altered. The land occupation for expansion of the treatment facility is also cut-off, it is assumed that the facility can be built on the present wastewater treatment facility. Further, equipment used in the separation and treatment process and in the Re-plex production process is cut-off. It is assumed that this contributes very little to the environmental impacts, and is cut-off due to a time constraint.

4.2.3 Flowcharts

Below the flowcharts for the two alternatives are given (figure 3). One for production and use of the Re-plex composite, one for the production and use of a FR-MDF composite. An inventory table with the in- and outflows into each foreground process is given in the Appendix. For the background processes from the Ecoinvent database consult the supplementary inventory excel file.

A:



B:

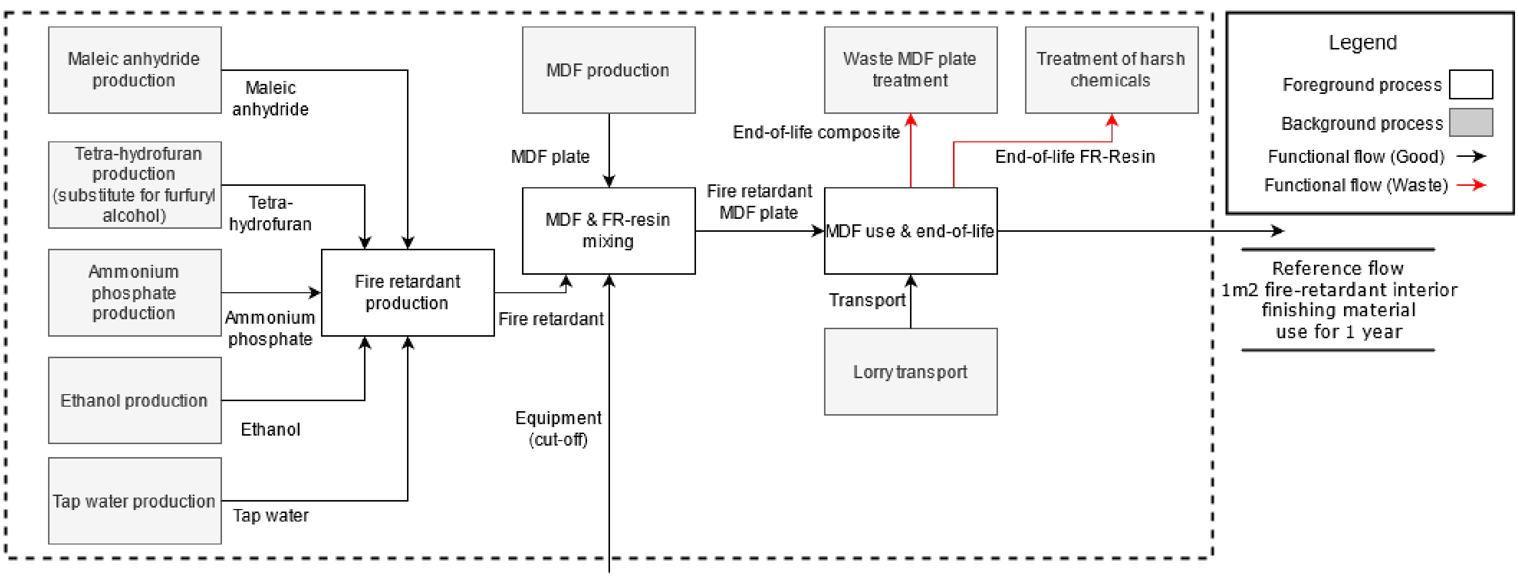


Figure 3: flowcharts for the LCA model. A: flowchart for the Re-plex composite. B: Flowchart for the FR-MDF composite.

Re-plex flowchart

The production of Re-plex starts with the waste flow Nereda® wastewater sludge at a wastewater treatment facility. Unlike mechanical dewatering used in standard wastewater sludge treatment, the sludge is gravitationally thickened until 4% dry weight. Thus this process requires no addition of electricity or heat. Before further sludge treatment, the Kaumera polymer is extracted by the addition of sodium carbonate. The extraction process takes place at 80C, requiring the addition of heat. Electricity is required for operation of the stirring equipment, and the centrifuge equipment to separate the product Na-bound Kaumera from the sludge residue.

The sludge residue is treated using anaerobic digestion. This process requires heat and electricity for operation, and produces biogas and the waste biomass residue. The biogas in burned in a combined heat and power plant, producing electricity and heat from anaerobic digestion to be used within the sludge treatment facility. The biomass residue is transported to a residue treatment facility. Here the biomass residue is mechanically dewatered using electricity and polyelectrolyte, producing dry biomass residue. The dry biomass residue is burned in an incineration process. This produces electricity from anaerobic digestion similar to the biogas incineration.

The Na-bound Kaumera is precipitated by the addition of Hydrochloric acid, electricity is used for centrifugation to produce Kaumera gel. The Kaumera gel is transported to a Re-plex production facility. The Kaumera gel is partially dried using a spray dryer which requires heat and produces Dry Kaumera.

The base materials for the production of Re-plex are cellulose, Kaumera gel and dry Kaumera. Other stabilizing materials to enhance material properties are added (glycerol, sorbitol and citric acid). All these materials require transport to the Re-plex production location. Further, the Re-plex production process requires electricity for the operation of an oven and a press. This process produces a plate of Re-plex. The Re-plex plate is subsequently used in a use process. This includes transport to the customer and the end-of-life treatment for used Re-plex plate waste. It is assumed that the plate will be treated similar to waste wood with municipal incineration. The process produces the function 1m2 of fire retardant interior finishing material use for 1 year. The lifetime of Re-plex is assumed to be similar to MDF, which is 32 years (S. Picken, personal communication, 14 June 2021).

MDF flowchart

The MDF flowchart starts with the production process of a fire retardant resin. This FR-resin is produced by addition of the chemicals maleic anhydride, tetra-hydro furan, ammonium phosphate, Ethanol and water. The FR-resin is impregnated on MDF plate in the MDF and FR-resin mixing process to produce FR-MDF. The FR-MDF is transported to the consumer in the MDF use process. The end-of-life treatment for used FR-MDF waste is included. It is assumed that the MDF plate will be treated similar to waste wood, while for the FR-resin the waste treatment of harsh chemicals is assumed. The process produces the function 1m2 of fire interior interior finishing material use for 1 year.

4.2.4 Data collection and assumptions

Data on the foreground processes of the Re-plex alternative is collected by desk research and interviews with engineers working on the development of Re-plex. As well as interviews with suppliers of the materials for the production of Re-plex. Data collection on the foreground processes for the MDF alternative has been collected solely by desk research.

For the desk research the TU Delft library Worldcat database is used. All the assumptions and data sources for the assumptions are summarised in the Appendix. The most important assumptions are also discussed below. First the assumptions for Re-plex are discussed, second the assumption for MDF are discussed. Lastly, the datapoints with low reliability are discussed.

Data on the separation of Kaumera from the Nereda® wastewater sludge is obtained from the LCA by Ecoras for the 2016 STOWA report; LCA on materials from domestic wastewater (S. Jurgens, personal communication, 30 March 2021; Visser et al., 2016). This includes the electrical- and heat energy use and the chemicals (sodium carbonate, chloric acid) use in the separation of Kaumera gel from the wastewater sludge. The further treatment of the wastewater sludge by anaerobic digestion is also based on Visser et al. (2016). One deviation is that anaerobic digestion and Kaumera separation facility is assumed to be on the WWTP site instead of at the sludge incineration site. This results in less transport of sludge to the sludge incineration site. The mass balances and energy recovery balances from the anaerobic digestion have been calculated and validated (P. Kehrein, personal communication, 5 May 2021). The electrical- and heat energy balances and chemical (polyelectrolyte, lime) use in the anaerobic digestion of the sludge treatment is based on the data by Visser et al. (2016). Accidental biogas emissions to the environment during anaerobic digestion are not included in the model by Visser et al. (2016). Since the biogas is assumed to be 65% methane and 35% CO2 these emissions can be an important contributor to greenhouse gas emissions in anaerobic digestion. The emission of biogas is modelled to be 1% of the total amount of biogas produced during anaerobic digestion, similar to Pucker, Jungmeier, Siegl, & Pötsch, (2013). They based their model of biogas emissions on 0.5% biogas slip reported by Vogt (2008) and 1.79% reported by Woess-Gallasch et al. (2010). Further, CO2 emissions of sludge incineration are based on the assumption that all dry weight in the sludge residue is in the form of biomass with the molecular formula $CH_{1.77}O_{0.49}N_{0.24}$ (Grosz & Stephanopoulos, 1983).

Further handling of the Kaumera gel to produce Re-plex is modelled based on desk research and expert interviews. Three important components added in the Re-plex production are glycerol, sorbitol and citric acid. Since sorbitol production was not available in the Ecoinvent database, it has been substituted by glucose. Besides these three components, Kaumera gel, dry Kaumera and cellulose are part of the Re-plex formulation. Data on Re-plex formulation is obtained from COMPRO project members, Peter van Mooij from the Amsterdam Metropolitan Institute (AMS) (P. Mooij, personal communication, 24 February 2021). The electrical energy requirements of Re-plex production are obtained from Mark Lepelaar. Re-plex is produces by mixing the ingredients to form a dough. The Re-plex dough is cured in an electrical oven at 75C for 3 to 4 hours, after which it is pressed at 10 Bar at 145C to 160C for 45 minutes (M. Lepelaar & I. Jansen, personal communication, 24 March 2021).

The transport requirements for the raw materials have been calculated based on source locations and transport distances to the Re-plex production location Amsterdam. If transport was included in the background database, it is not added manually to avoid double counting. This was the case for all raw materials except Kaumera. For the other raw materials the market background processes have been used, which includes average transport requirements. The production location of the Kaumera gel is Zutphen, The Netherlands. The Kaumera gel is transported to Amsterdam, where it is dried to produce dry Kaumera and where the Re-plex is produced. This transport distance is 108km.

Dry Kaumera is produced by drying the Kaumera gel at the Re-plex production location in Amsterdam. The Kaumera gel has a dry weight of 7% according to Robbert Binnenveld from Chaincraft (R. Binnenveld, personal communication, 5 March 2021). Chaincraft is the Kaumera gel producer. The energy usage of this process is not known by Chaincraft. Therefore average spray drying energy requirements, 4.87GJ/ton water, are used to model the heat requirement for this process (Baker & McKenzie, 2005).

For the cellulose added to Re-plex, a background process is used. In reality the cellulose is produced by Recell® from recycled cellulose fibres from domestic wastewater treatment. However, due to time constraints the Recell® process is not modelled and instead standard cellulose production from waste paper is used. According to Yme Flapper from Recell® and the STOWA the extraction and production of the cellulose product from the wastewater sludge is energetically favourable compared to baseline operation from a wastewater treatment perspective (Y. Flapper, personal communication, 31 March 2021; Remy, Conzelmann, Rey Martinez, & Benedetti, 2020; Winters, Pijlman, Maathuis, & Dinkla, 2013).

The thickness and density of Re-plex is obtained from Peter van Mooij (AMS). Re-plex density is 1.2g/cm3 and the thickness of the Re-plex plates is 8mm. This results in a 1m2 Re-plex plate having a weight of 9.6kg (P. Mooij, personal communication, 24 February 2021). The end-of-life process of Re-plex is assumed to be the same as for waste wood with municipal incineration.

The average thickness (12mm) and density (0.7g/cm3) for MDF has been obtained by desk research (Allesovermdf.nl, n.d.). This results in a 1m2 MDF plate with a weight of 8.4kg. The lifetime of an MDF plate is 32 years on average (Nakano, Ando, Takigawa, & Hattori, 2018).

The production of MDF is available in the Ecoinvent database, this process includes a small addition of Fire-retardant. It is assumed however, that a higher fire rating (A or B European fire-rating), comparable to Re-plex, can only be obtained by adding a full fire-retardant coating. For this fire retardant coating a coating based on Maleic anhydride and polymerization of furfuryl alcohol with ammonium phosphate is used. The formulation of this coating is based on experimental data by Kong, Guan, & Wang (2018). This formulation includes ethanol, maleic anhydride, ammonium phosphate, water and furfuryl alcohol. The furfuryl alcohol is not present in the Ecoinvent database. It is substituted by tetra-hydrofuran, which is produced by hydrogenation of furfuryl alcohol. 0.4kg of FR-resin is added, similar to the amount used to obtain maximal fire-retardancy by Ma, Wu, & Zhu (2013). No energy usage is assumed for the addition of the FR-resin to the MDF plate. This is because the background MDF production process already includes energy usage for mixing and pressing of the raw materials to produce the MDF plate.

Formaldehyde emissions of MDF during its use phase are an important contributor to its human health impact (Nakano et al., 2018). To model this emission the logarithmic emission equation of Nakano et al. (2018) is used. It is assumed that European MDF has the Japanese F*** rating for formaldehyde emissions (0.07mg/m3). This correspond with a rating under the European formaldehyde emission limit (0.10mg/m3) (Ruffing, 2011). Calculations of the formaldehyde emissions can be found in the Appendix. The end-of-life process for FR-MDF is assumed to be waste fibreplate. However, for the weight of FR-resin used (0.4kg), treatment of hazardous waste is assumed since the treatment of these chemicals is important to avoid bio-accumulation of toxic compound (van der Veen & de Boer, 2012).

Some data points have a large uncertainty and is heavily based on assumptions. These are shortly discussed here. The assumed lifetime for both the Re-plex plates, as well as the MDF plates is 32 years. Although for Re-plex, this lifetime is an estimation. Since this product is not yet used for such timescales it is unclear if this assumption will hold. According to S. Picken (personal communication, 14 June 2021), the lifetime of Re-plex should be at least as long, if not longer than for MDF. However, if the lifetime of Re-plex is not feasible on such timescales the application as interior finishing material will not be economically feasible since the building would need to be renovated before the average time of 32 years. Still, the sensitivity of the lifetime of Re-plex on the impact assessment is be quantified in the sensitivity analysis. Transport of both interior finishing materials Re-plex and FR-MDF to the building location is assumed to be 100km on average. This is an assumption on the average transport of building materials from the producer to the building site.

4.2.5 Multi-functionality and allocation

Some processes in the product system of Re-plex perform multiple functions, and are thus multifunctional. These processes are part of multiple product systems. To determine the system boundaries between these multiple product systems, the multifunctionality needs to be solved. This can be done either by subdivision, system expansion, cut-off, substitution or allocation (European Commission et al., 2011). In subdivision, the multifunctional process is studied in more detail and split up into two processes, each providing one of the functions of the whole process. In system expansion the product system is expanded to produce both functions in one product system. In cut-off, the co-function of the product system is not taken into account and all flows are considered to be part of the primary function. In substitution, the co-function is assumed to be able to substitute an existing process. Subsequently, the flows of this existing process are subtracted from the multifunctional process. In allocation, the flows of the multifunctional process is split over the two functional flows based on a partitioning method. This is a virtual subdivision, the two virtual parts of the multifunctional process are considered to be part of a different product system.

In the case of Re-plex production there are four multifunctional processes. The multifunctionality is solved by using energy based partitioning in this LCA. In this case all non-functional flows of the processes that are needed for both the sludge treatment and Kaumera production is allocated between wastewater sludge treatment and the Kaumera production; Allocated between the sludge treatment and biogas production in anaerobic digestion; Allocated between the electricity and heat produced in biogas incineration; And allocated between sludge treatment and electricity production in sludge incineration.

The Nereda® wastewater sludge is a waste, since this is a flow from the Nereda® wastewater treatment plant that cannot be disposed of without further treatment due to strict regulations (Unie van Waterschappen, 2019). While the Na-bound Kaumera and subsequent product Kaumera gel is a good, since this can be used as a raw material for a wide range of products. The multifunctional process performing both sludge treatment and Kaumera production is: Dissolve and separate Kaumera at production facility. The process Anaerobic digestion at sludge treatment facility treats the wastewater sludge, but also produces the good biogas, which is used for energy generation. The biogas incineration process produces the goods electricity and heat. These products are recycled within the product system (closed-loop), but also produced as co-products (open-loop). Last, the biomass residue incineration process delivers waste treatment for the sludge residue and produces the good electricity.

Table 2: Multifunctional processes and functional flows in the Re-plex product system. For the four multifunctional processes the allocation factors are calculated (see Appendix) based on energy content (energy allocation) and on product prices (economic allocation).

Multifunctional process	Functional flow 1	Energy allocation partition factor	Economic allocation partition factor	Functional flow 2	Energy allocation partition factor	Economic allocation partition factor
Dissolve and separate Kaumera	Kaumera gel	0.187	0.187	Sludge treatment	0.813	0.813
Anaerobic digestion	Biogas	0.798	0.025	Sludge treatment	0.202	0.975
Biogas incineration	Electricity	0.512	0.488	Heat	0.751	0.249
Residue incineration	Electricity	0.886	0.941	Sludge treatment	0.114	0.059

The allocation based on the energy content of the wastes and product is used. It is best practice to keep the partitioning method the same for all multifunctional processes (European Commission et al., 2011). This implies that mass based allocation is not possible since heat and electricity produced have no mass. Physical allocation is preferred over economic allocation since the prices of the waste treatment and the Kaumera are hard to determine and can differ significantly regionally. Still, economic allocation is used in a sensitivity analysis. The multifunctional processes, the functional flows and the allocation results are summarised in table 2. Calculations for the allocation factors can be found in the Appendix.

4.2.6 Results inventory analysis & completeness check

The inventory analysis resulted in an overview of the inflows and outflows of materials and energy for the product system of Re-plex. Important to note is that capital goods are out of scope, buildings, fermentation tanks and extraction equipment are not included in the inventory. The values for in- and outflows of the foreground processes can be found in the Appendix. The total inventory overview with background processes for the product systems can be found in the supplementary excel file.

A completeness check is performed to determine if the inventory meets the requirements in the goal and scope definition. In the completeness check the processes and elementary flows of the product system are judged for quality and the completeness is estimated. The process coverage of the product systems is assessed. It is concluded that all relevant processes have been included in the system, only capital good (buildings, concrete tanks, equipment) have not been included in line with the cut-off criteria. Further, for background processes preferably the market process has been used, this includes transport, for other processes the transport is modelled manually. It is expected that the self-modelled transport better represents reality. Process data on citric acid is aggregated. This results in a unit process that is not linked to the respective unit processes in the background database. This makes the applicability of a contribution analysis on process level less informative than would be the case for a non-aggregated process.

For two chemicals a substitute that is a precursor to the chemical is used, but since these two chemicals are used in small amounts, this is not expected to have considerable effects on the inventory. The technological, geographical and time-related representativeness are applied as described in the goal & scope, the processes need to be close to the current technology level and be according to preference Dutch, European, and global scope.

For the cellulose production a background process is used, producing cellulose from waste paper. In reality Recell®, a cellulose product recovered from wastewater is used. It is expected that the environmental impacts of Recell® are lower than for cellulose from waste paper (Y. Flapper, personal communication, 31 March 2021; Winters et al., 2013). However, due to a time constraint the Recell® process has not been modelled.

The lifetime for both Re-plex and FR-MDF is assumed to be 32 years. However, this could be significantly longer, to a timescale of 40 years lifetime for MDF (Nakano et al., 2018). Similar lifetimes are expected for Re-plex (S. Picken, personal communication, 14 June 2021). Still, the influence of RE-plex' lifetime is identified in the sensitivity analysis. The production of the FR-resin is based on experimental data (Kong et al., 2018; Ma et al., 2013). Therefore the use of the FR-resin can be overestimated compared to best practice in a market scenario.

Overall, all relevant process have been included and the completeness of the process coverage is expected to be >90% complete.

Elementary flow coverage is not fully complete. For the most part background processes are used in the LCA model, which can be expected to be close to 100% complete. However, for the foreground processes only the elementary flows are included which are expected to have a significant contribution to the characterisation. These are the biogas slip during the anaerobic digestion of sludge residue, CO2 emitted during incineration of biogas and sludge residue, and the formaldehyde emissions during the use phase of FR-MDF. For the incineration processes complete incineration of the carbon is assumed and no other emissions are included. Therefore the elementary flow coverage is expected to be >90% complete.

Further, 780 emissions do not have characterisation factors in the ILCD impact family (Supplementary excel file). Thus they do not contribute to any impact category. This includes the CO2 emissions of the biogas and sludge residue incineration processes, because these are non-fossil CO2 emissions. Which flows do not have characterisation factors is dependent on the impact assessment models used in the impact assessment family. Emissions of non-fossil CO2 are not included in the ILCD characterisation factors (European Commission et al., 2011). In the sensitivity analysis the ReCiPe impact assessment family is used for comparison.

4.3 Impact assessment results and discussion

In the impact assessment phase the total inventory of emissions is used to calculate the environmental impact that the product system has. The impact categories and the contribution of environmental flows to the impact categories depends on the impact assessment family used. In this LCA the ILCD 1.0.8 2016 impact assessment family is used because this is the standard family of the European Union (European Commission et al., 2011).

The ILCD impact assessment family uses 4 endpoint indicators; climate change, ecosystem quality (EQ), human health (HH) and resources (RC). These 4 endpoint indicators are divided up into 15 midpoint indicators. Only the 15 midpoint indicators is, since weighing of midpoint categories to endpoint indicators always involves a value judgement of the relative importance of impact categories. There cannot be scientific consensus on how to do this (Pizzol et al., 2017). The 15

Table 3: Impact categories, impact models and impact indicators used in the ILCD 2011 methods.

Impact category	model	characterisation factor
Climate change	(IPCC, 2007)	Global warming potential 100 years (GWP_{100})
Ecosystem quality -freshwater and terrestrial acidification	(Posch et al., 2008; Seppälä, Posch, Johansson, & Hettelingh, 2006)	Accumulated exceedance (AE)
Ecosystem quality - freshwater ecotoxicity	USEtox (Rosenbaum et al., 2008)	Comparative toxic unit for ecosystems (CTUe)
Ecosystem quality - freshwater eutrophication	EUTREND model (Goedkoop, Heijungs, Huijbregts, Struijs, & van Zelm, 2009)	P- and N-equivalents
Ecosystem quality - ionising radiation	(Garnier-Laplace et al., 2009)	CTUe
Ecosystem quality - marine eutrophication	EUTREND model (Goedkoop, Heijungs, Huijbregts, Struijs, & van Zelm, 2009)	P- and N-equivalents
Ecosystem quality - terrestrial eutrophication	(Posch et al., 2008; Seppälä, Posch, Johansson, & Hettelingh, 2006)	AE
Human health - carcinogenic effects	USEtox (Rosenbaum et al., 2008)	Comparative toxic unit for human health (CTUh)
Human health - ionising radiation	(R. Frischknecht, Braunschweig, Hofstetter, & Suter, 2000)	Ionizing radiation potentials
Human health - non-carcinogenic effects	USEtox (Rosenbaum et al., 2008)	CTUh
Human health - ozone layer depletion	(WMO, 1999)	Ozone depletion potential (ODP)
Human health - photochemical ozone creation	(van Zelm et al., 2008)	Photochemical ozone creation potential (POCP)
Human health - respiratory effects, inorganics	RiskPoll model (Rabl & Spadaro, 2004)	Mass PM-2.5-equivalents
Resources - land use	(Milà i Canals et al., 2007)	Soil Organic Matter (SOM)
Resources - mineral, fossils and renewables	(van Oers, de Koning, Guinee, & Huppes, 2002)	Abiotic depletion potential (ADP)

midpoint indicators used in the LCA are; Climate change; EQ, freshwater and terrestrial acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ, ionizing radiation; EQ, marine eutrophication; EQ, terrestrial eutrophication; HH, carcinogenic effects; HH, ionizing radiation; HH, non-carcinogenic effects; HH, ozone layer depletion; HH, photochemical ozone creation; HH, respiratory effects, inorganics; RC, land use; and RC, mineral, fossils and renewables.

The impact assessment models and the corresponding characterisation factors are summarized in table 3. A detailed discussion on the impact models and deviations from these models can be found in the Database and supporting information of the ILCD Life Cycle Impact assessment methods (European Commission, Joint Research Centre, 2012).

4.3.1 Classification

A classification analysis is performed for both product systems. This aggregates the emissions of the product systems per impact category, resulting in a list of all emissions contributing to the impact category. The result of the classification for the product system of 1 year of Re-plex use and 1 year of FR-MDF use can be found in the supplementary Excel file.

4.3.2 Characterisation

A characterisation analysis is performed for both product systems. In this analysis the classified emissions are summed to one unit per impact category using the characterisation factors. This results in the impacts for both product systems (table 4). In most impact categories (14 out of 15) the FR-MDF use performs better than Re-plex use. In one impact category the Re-plex use performs better; HH, respiratory effects.

For a clear overview the characterisation results of both product systems have been normalized to the highest value of both systems, this is set to 100% (Figure 4). This gives a better overview of the difference between the characterisation results for Re-plex use and FR-MDF use. In 3 impact categories the impact results of Re-plex and FR-MDF are nearly the same (difference <10%). In the impact categories HH, carcinogenic effects; and HH, photochemical ozone creation the characterisation result of FR-MDF is 10% and 2% lower than for Re-plex respectively. In the impact

Table 4: ILCD Characterisation results for 1 year of 1m2 Re-plex use and 1 year of 1m2 FR-MDF use.

Impact category	1 year 1m2 Re-plex use	1 year 1m2 FR-MDF use	Unit
Climate change	0.699	0.401	kg CO2-Eq
EQ. acidification	0.00412	0.00241	mol H+-Eq
EQ. freshwater ecotoxicity	5.45	3.45	CTUh.m3.yr
EQ. freshwater eutrophication	0.000271	0.000116	kg P-Eq
EQ. ionising radiation	1.81E-07	1.07E-07	mol N-Eq
EQ. marine eutrophication	0.00106	0.000596	kg N-Eq
EQ. terrestrial eutrophication	0.00901	0.00645	mol N-Eq
HH. carcinogenic effects	3.51E-08	3.16E-08	CTUh
HH. ionising radiation	0.0625	0.0245	kg U235-Eq
HH. non-carcinogenic effects	2.16E-07	1.46E-07	CTUh
HH. ozone layer depletion	8.01E-08	4.00E-08	kg CFC-11-Eq
HH. photochemical ozone creation	0.00167	0.00163	kg ethylene-Eq
HH. respiratory effects. inorganics	0.000457	0.000477	kg PM2.5-Eq
RS. land use	119	3.54	kg Soil Organic Carbon
RS. mineral. fossils and renewables	7.24E-05	1.53E-05	kg Sb-Eq

category HH, respiratory effects, inorganics the characterisation result of Re-plex is 4% lower than for FR-MDF.

In two impact categories Re-plex performs much worse than FR-MDF (difference >70%). in the RC, land use; and RC, minerals impact category respectively, the characterisation result of FR-MDF use is 97% and 78% lower than for Re-plex use. In the other 10 impact categories the FR-MDF has 27%-61% lower characterisation results than Re-plex.

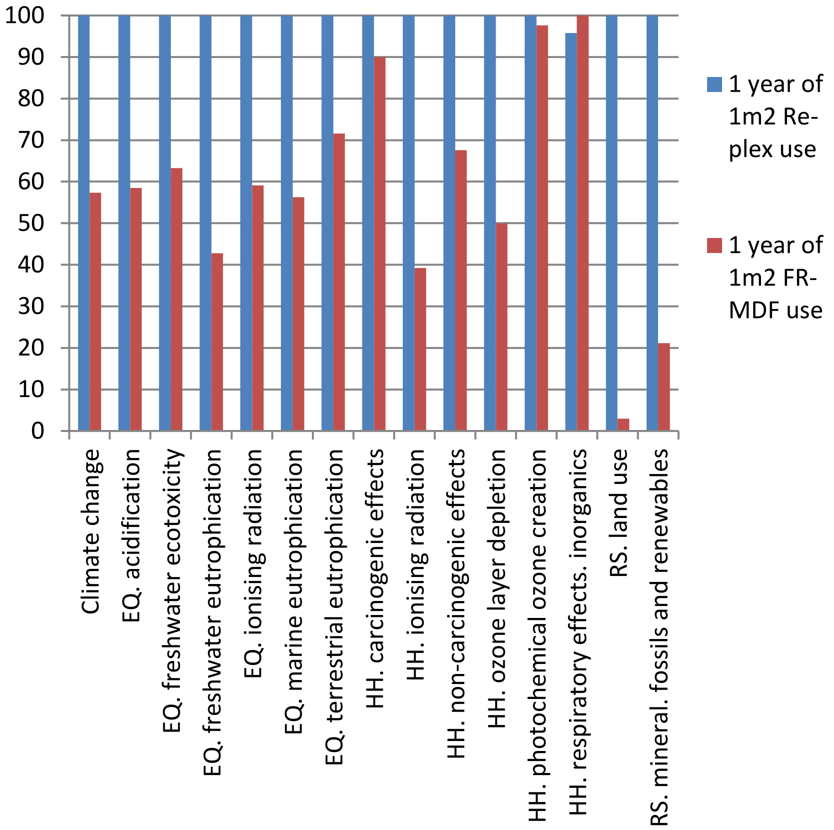


Figure 4: Normalisation of characterisation results to the highest value of the two product systems. Blue indicates 1 year 1m2 Re-plex use and red indicates 1 year 1m2 FR-MDF use.

4.3.3 Normalisation

The characterisation results of 1 year of Re-plex use and 1 year of FR-MDF use are normalised to the total ILCD characterisation result of the domestic emissions in the EU-27 in 2010 (Benini et al., 2014) (Figure 5). This is done to compare the impacts of both product systems in the same unit, namely the impacts relative to the total impacts in the EU. In this way it is determined to which impact categories the contribution of Re-plex and FR-MDF is relatively large compared to the impacts within the EU.

The normalised characterisation results compared to the EU domestic characterisation results are not very high for all 15 impact categories. However; EQ, freshwater ecotoxicity; HH, carcinogenic effects; RC, land use; and RC, mineral, fossil and renewables jump out as a high impact categories with normalisation results over 10^-12. Still, all normalised results fall in the range of 10^-15 to 10^-11 compared to the EU-27 total domestic characterisation results. As would be expected the contribution of 1m2 of interior finishing material use should not have significant emissions on European scale.

The impact category; EQ, ionizing radiation does not have totals in the ILCD normalisation method (Benini et al., 2014). The normalisation method does not include this impact category as this is not a score I or II recommended impact category of the ILCD impact family (European Commission, Joint Research Centre, 2012).

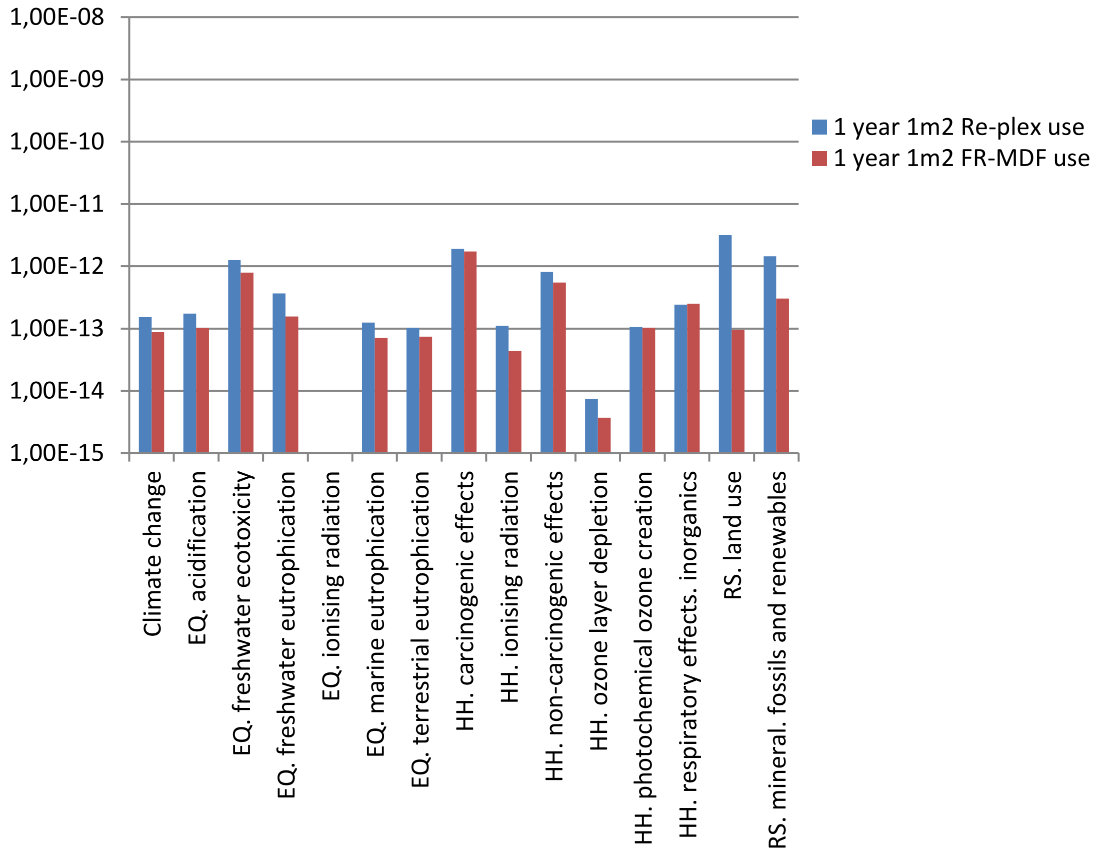


Figure 5: Total characterisation results of Re-plex use and MDF use normalised to the 2010 EU domestic characterisation results according to the ILCD normalisation methods by Benini et al. (2014).

4.3.4 Contribution analysis

In the contribution analysis the contribution of all background processes to the impact categories for both product systems is determined. For every unit process the characterisation results are calculated and compared to the characterisation result of the total product system. This shows which processes contribute the most to the impact categories. The contributions of all unit processes to the characterisation results for both product systems are given in the supplementary excel file.

Next to the standard contribution analysis, a stage contribution analysis is performed. In a stage contribution analysis the product system is divided up into arbitrarily chosen stages in the product system. All processes in a stage are aggregated to a single characterisation result, and compared to the total characterisation result of the product system. To get a better understanding of which stages in Re-plex production contribute the most to the total impacts, a stage contribution analysis is performed. This enables the identification of hotspots in emissions in the product-system of Re-plex production.

Background process contribution analysis

The results for the standard contribution analysis can be found in the supplementary excel file. Notable results from the standard contribution analysis are that citric acid production processes, especially its production process in China, is present in all impact categories. This is due to the aggregated nature of this process, resulting in high environmental emissions of this process. The citric acid production process is aggregated, meaning that all processes required for citric acid production are included in one unit process instead of connected to other background unit processes. The aggregated citric acid production processes are the most contributing processes, making the background contribution analysis not very insightful. Therefore the use of a stage contribution analysis is more elucidating on hotspots of emissions in Re-plex production and use.

Stage contribution Re-plex production

The stages that are derived for the Re-plex production process are cellulose production, glucose production, glycerine production, citric acid production, electricity production, Transport of Re-plex to the installation site, Kaumera production and transport, and the Re-plex end-of-life treatment.

These stages are implemented in CMLCA as product systems. The contribution of these stage

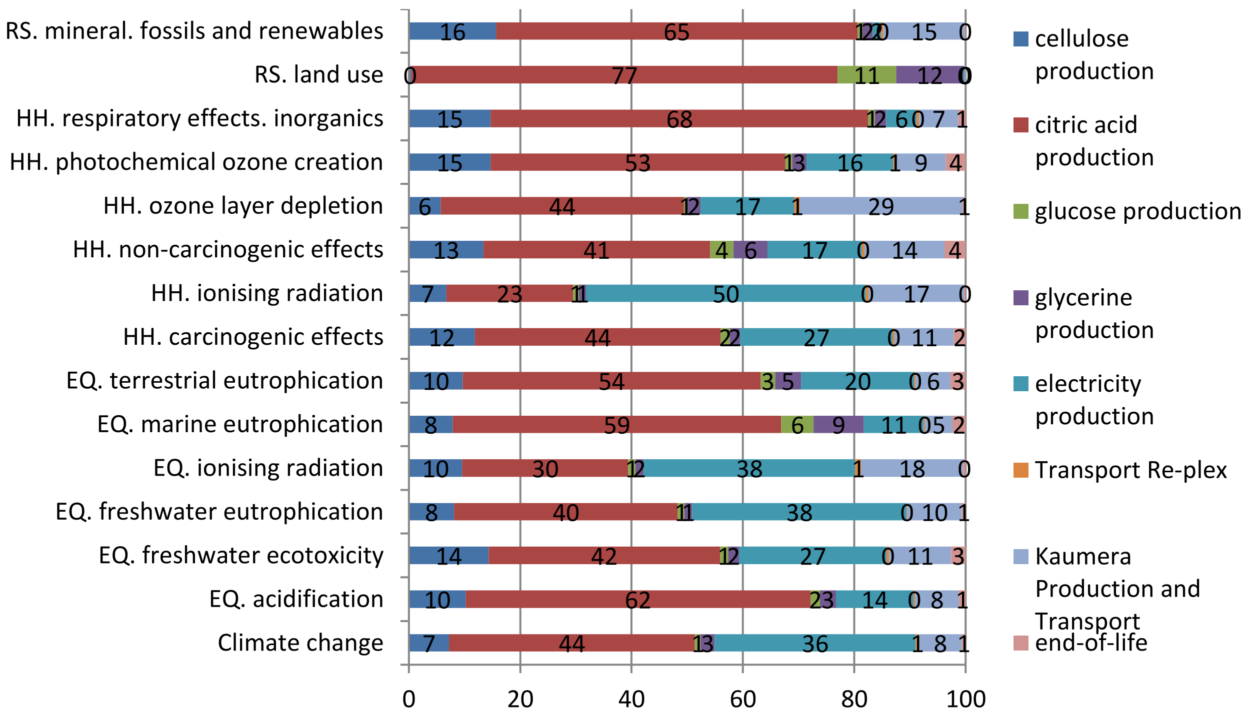


Figure 6: Contribution of set stages of Re-plex production and use to the characterisation results of the 15 impact categories.

product systems needed to produce Re-plex to the total characterisation results are calculated (Figure 6).

From this figure it is clear that citric acid dominates the characterisation results in most impact categories, with impacts between 22% and 77% of the total Re-plex production. Especially in the categories; Resources, minerals, fossils and renewables and Resources, land use the contribution of citric acid production is large with 65% and 77% respectively. Further Kaumera, Cellulose and Electricity have significant contributions to the total impacts. Kaumera contributes between 0% and 29% of the Re-plex characterisation results, but the Re-plex material consist mainly of Kaumera (52w%). Therefore the contribution of Kaumera to the characterisation results is small compared to the amount of Kaumera used in Re-plex. Cellulose contributes 6% to 16% to all impact categories except Resources land use, where it contributes 0%. The Re-plex material consists of 28w% cellulose. Therefore the contribution of cellulose to the characterisation results is small compared to the amount of cellulose used in Re-plex. Important to note however, is that the cellulose used in the model is coming from waste paper, while in reality cellulose from the company Recell® is used, which produces cellulose from domestic wastewater. The Recell® process is expected to perform better than the cellulose from waste paper (Remy et al., 2020). Therefore the contribution of cellulose production to the characterisation results is expected to be lower than the model suggests. Electricity use contributes between 11% and 39% in almost all impact categories. Only in the impact categories; HH, respiratory effects inorganics; RS, land use; and RS, mineral, fossils and renewables the contribution of electricity use is 6%, 0% and 2% respectively. Glucose and glycerine are used in such small quantities that these contribute little (0%-6%) to the Re-plex characterisation results. Only in the impact categories; EQ, marine eutrophication; and RS, land use do these two materials contribute relatively much, with 6% and 11% respectively for glucose production and 9% and 12% respectively for glycerine production to the characterisation results. Further, the transport of Re-plex to the installation site only has a small contribution to the Re-plex characterisation results (0%-1%). The end-of-life of Re-plex also has a small contribution to the Re-plex characterisation result (0%-4%).

From this stage contribution analysis hotspots in environmental impacts for Re-plex production and use can be derived. Since citric acid is the main contributor to the Re-plex characterisation results in almost all impact categories, this is the main focus for new Re-plex production scenarios. Further, the electricity usage during Re-plex production is a large contributor to the characterisation results. However, this is due to the process still being at lab scale. The equipment used does not have industrial efficiency and there is no focus on minimizing energy usage yet (M. Lepelaar & I. Jansen, personal communication, 24 March 2021). Scenarios are developed accounting for improvements in energy efficiency for a Re-plex production process on market scale. Third, although the contribution of Kaumera is low relative to the amount added to Re-plex, it still has a significant contribution to the characterisation results. Therefore improvements in efficiency of Kaumera production are also studied in the scenario development of Re-plex production.

4.3.5 Scenario analysis

The production process of Re-plex is still in development. A final application, the formulation and production process is not yet defined. To aid engineers in finding solutions that have less environmental impact than the current Re-plex product, scenarios are developed to improve the environmental performance of Re-plex. From the hotspot analysis it is clear that the main focus for the development of scenarios should be on the use of citric acid, energy usage during production and the production of Kaumera.

Since the use of citric acid has a high contribution to the characterisation results of Re-plex use, it is expected that the environmental performance of Re-plex can be improved by replacing the citric acid by some other component. The function of the citric acid in the Re-plex is the crosslinking of Kaumera with cellulose. This is done by esterification of Kaumera and cellulose with the acid functional groups in citric acid. Citric acid is added in stoichiometric amount (Jure Zoplasa, personal communication). Citric acid can in theory easily be replaced by other tri- and di-carboxylic acids. LCAs on the use of citric acid as additive in fibreplates are scarce. In one LCA Essoua, Beauregard, Amor, Blanchet, & Landry (2017) find that the use citric acid in softwood treatment has higher environmental impacts than using terephthalic acid.

The alternative tri- and di-carboxylic acids in the Ecoinvent database are succinic acid and adipic acid. The stoichiometric amounts of these acids that can replace the citric acid are compared on the 15 ILCD impact categories (see Appendix). From this analysis it is clear that the impacts of citric acid are higher than for the other two acids, especially in the impact category; RS, land use. The succinic acid performs best of the three acids. Therefore a scenario in which succinic acid is used for the cross-linking is developed. Instead of using 15.7kg of citric acid in the standard Re-plex production, 9.6kg of succinic acid is used in the new Re-plex production scenario.

A second method to reduce the use of the carboxylic acid in Re-plex is to change the Re-plex recipe and include more of other components. The addition of cellulose to Re-plex can be increased from 28% to 40%, reducing the use of all other materials in equal amounts. However, since the improvements obtained from this change in Re-plex recipe depends on the carboxylic acid used, it is implemented in the New Re-plex production scenario with all improvements to the production process combined.

The energy use during Re-plex production is expected to decrease over time until market introduction. This would be due to scaling up and a focus on improving efficiency in the production process. It is assumed that the energy usage of Re-plex production can become equal to that of MDF per m2 plate material produced. The MDF is pressed and baked in a process similar to the production of Re-plex. Moreover, for MDF the energy usage would probably even be higher since the pine wood used in MDF needs to be cut in small pieces. While for Re-plex readily available cellulose from secondary sources (Recell®) is used. The Recell® cellulose does not require mechanic shredding before plate production. The standard energy usage for Re-plex production is 143 kWh electricity per 100kg Re-plex. The new energy usage is 28 kWh electricity and 140 MJ heat per 100kg Re-plex.

A third scenario is developed for the transport of the Kaumera to the Re-plex production location in Amsterdam. In the current production process the Kaumera gel is transported in wet condition to the Re-plex production location in Amsterdam. Here it is (partly) dried and added to the Re-plex formula as dry Kaumera. An obvious reduction in impact is realizable by drying the Kaumera on-site, and transporting the dry Kaumera to Amsterdam. This decreases the transport requirement from 52 Ton*km per 100kg of Re-plex produced in the standard Re-plex production process to 6 Ton*km per 100kg of Re-plex produced in a new Re-plex production scenario.

For the three new Re-plex production scenarios the changes are implemented in the inventory of standard Re-plex, and the characterisation results are calculated (see Appendix). The resulting changes in characterisation results for these three scenarios are normalized to standard Re-plex production, these results can be seen in figure 7.

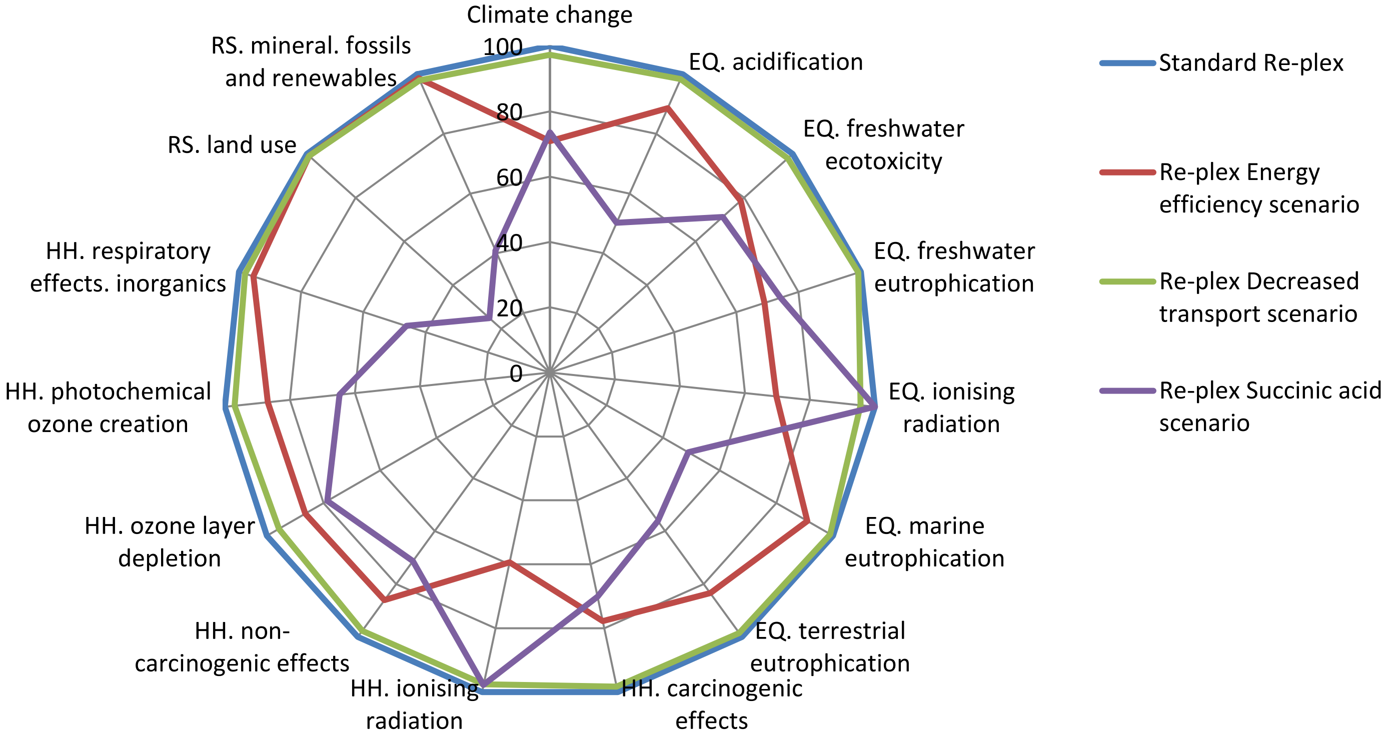


Figure 7: Normalised characterisation results of the Re-plex production process scenarios in a spider graph. The Re-plex production scenarios are normalised to standard Re-plex production (blue). Re-plex production scenarios with; Improved energy efficiency (red); Decreased transport requirements (green); and Succinic acid as crosslinker (purple).

From this figure it is clear that the change of citric acid to succinic acid is the main driver in reducing the impact of Re-plex. In most impact categories the succinic acid scenario is able to decrease the characterisation results of Re-plex the most. Especially in the impact categories; RS, land use; RS, mineral, fossils and renewables; and EQ, marine eutrophication using succinic acid is able to decrease characterisation results. While the other two scenarios (Energy efficiency, Decreased transport) are not able to obtain significant reductions in impacts in these categories.

Improved energy efficiency is able to reduce the impacts of standard Re-plex in all impact categories. Especially in the impact categories: EQ, ionizing radiation; and HH, ionizing radiation improved energy efficiency is able to decrease impacts more than the other two scenarios (Decreased transport, Succinic acid crosslinker).

The reduced transport scenario not able to decrease the characterisation results very much. Still, it results is small improvements in the characterisation results compared to standard Re-plex production.

The improved energy efficiency, decreased Kaumera transport, and the use of succinic acid in the Re-plex production process are combined in a New Re-plex production scenario. This New Re-plex production scenario has again two options. Either adding 28% cellulose as in the standard model, or adding 40% cellulose. The addition of 40% cellulose results in Re-plex plate that is as strong as Re-plex with 28% cellulose (J. Zlopasa, personal communication, 21 May 2021). The characterisation results can be found in the Appendix. The characterisation results of these New Re-plex production scenarios are compared to the standard Re-plex production and FR-MDF production. The characterisation results are normalized to the standard Re-plex production model (Figure 8).

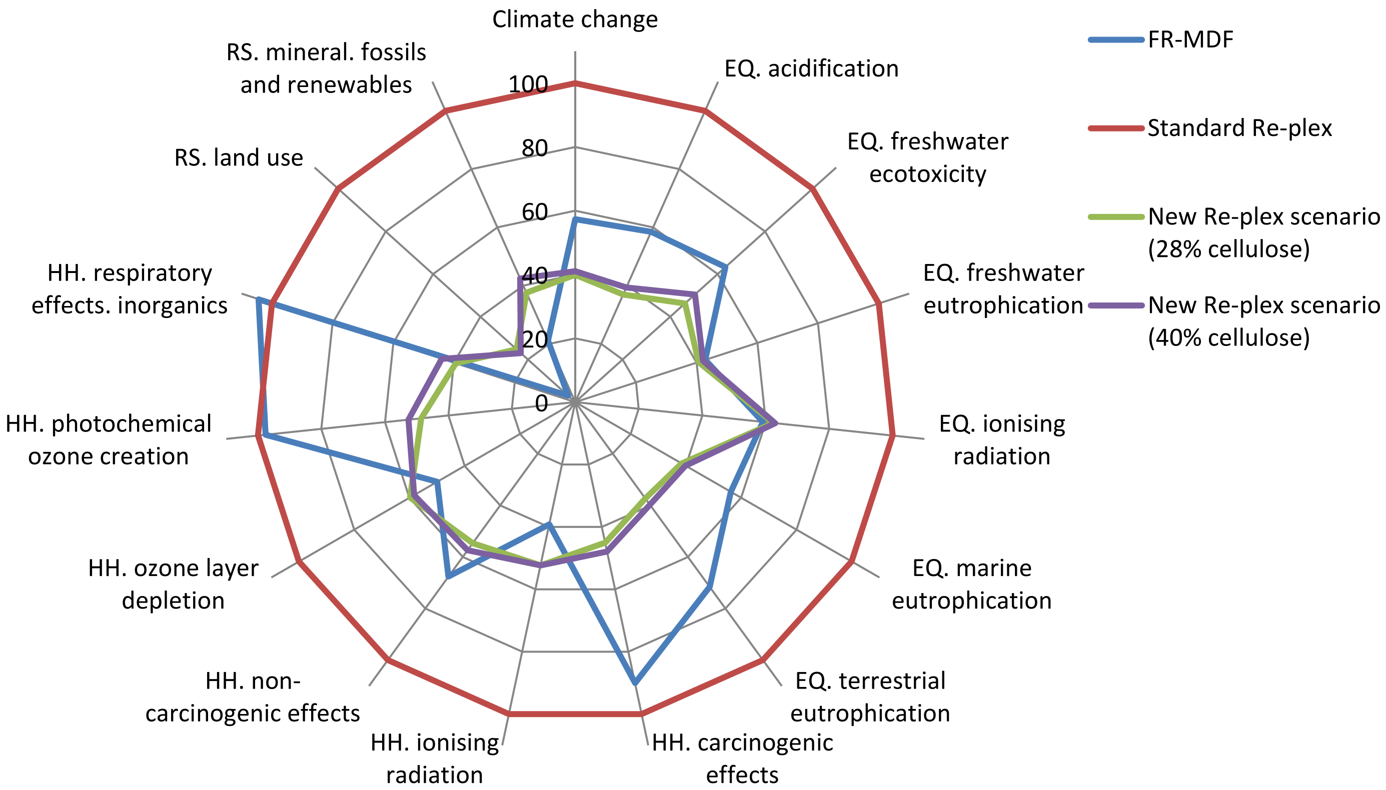


Figure 8: Normalised characterisation results of the New Re-plex production process and FR-MDF production (blue) in a spider graph. These production processes are normalised to standard Re-plex production (red). The New Re-plex production processes have decreased transport requirements, improved energy efficiency and use succinic acid as crosslinker compared to standard Re-plex production. One New Re-plex scenario has 28% cellulose in the Re-plex, as in standard Re-plex production (green). One New Re-plex scenario has 40% cellulose in the Re-plex (purple).

From this figure it is clear that both New Re-plex production scenarios perform much better than standard Re-plex production. When comparing both New Re-plex production scenarios (28% cellulose and 40% cellulose), the addition of 40% cellulose results in an increase in characterisation results in 13 impact categories. Only in the HH, ozone layer depletion; and the RS, land use impact categories does the 40% cellulose scenario decrease characterisation results. Still, the characterisation results are very similar for both scenarios. However, for cellulose production a background process using waste paper is used. While in reality Recell®, cellulose recovered from wastewater, is used. This results in inconclusive results on the use of cellulose in the Re-plex recipe. According to this model the addition of more cellulose to the Re-plex recipe does not decrease impacts. Therefore the New Re-plex production scenario (28% cellulose) is assumed to be the final New Re-plex production model. The impacts of Recell® compared to cellulose from waste paper is an important target for future studies. If Recell® has significant lower characterisation results than cellulose from waste paper, the addition of 40% cellulose to Re-plex would be beneficial to decrease the environmental impacts of Re-plex production and use.

The characterisation results for the New Re-plex scenario (28%) are compared to FR-MDF in Figure 9. The characterisation results are normalised to the alternative with the highest characterisation result, this is set to 100%. Compared to FR-MDF the New Re-plex production scenario (28% cellulose) scores better in the ten impact categories; Climate change; EQ, acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ, marine eutrophication; EQ, marine eutrophication; HH, carcinogenic effects; HH, non-carcinogenic effects; HH, photochemical ozone creation; and HH, respiratory effects, inorganics. Especially in the four impact categories; EQ, terrestrial eutrophication; HH, carcinogenic effects; HH, photochemical ozone creation; and HH, respiratory effects, inorganics, the New Re-plex scenario scores much better than the FR-MDF.

The FR-MDF scores better in the five impact categories; EQ ionizing radiation, HH, ionizing radiation; HH, ozone layer depletion; RS, land use; and RS, mineral, fossils and renewables. Especially in the two resources impact categories the FR-MDF still scores much better than the New Re-plex scenarios. While in the two impact categories EQ, freshwater eutrophication; and EQ ionizing radiation the characterisation results are almost equal.

The choice between New Re-plex and FR-MDF comes down to an assessment on the importance of the different impact categories. Still, based on the characterisation results it can be concluded that the New Re-plex scenario has a better overall environmental performance than the FR-MDF.

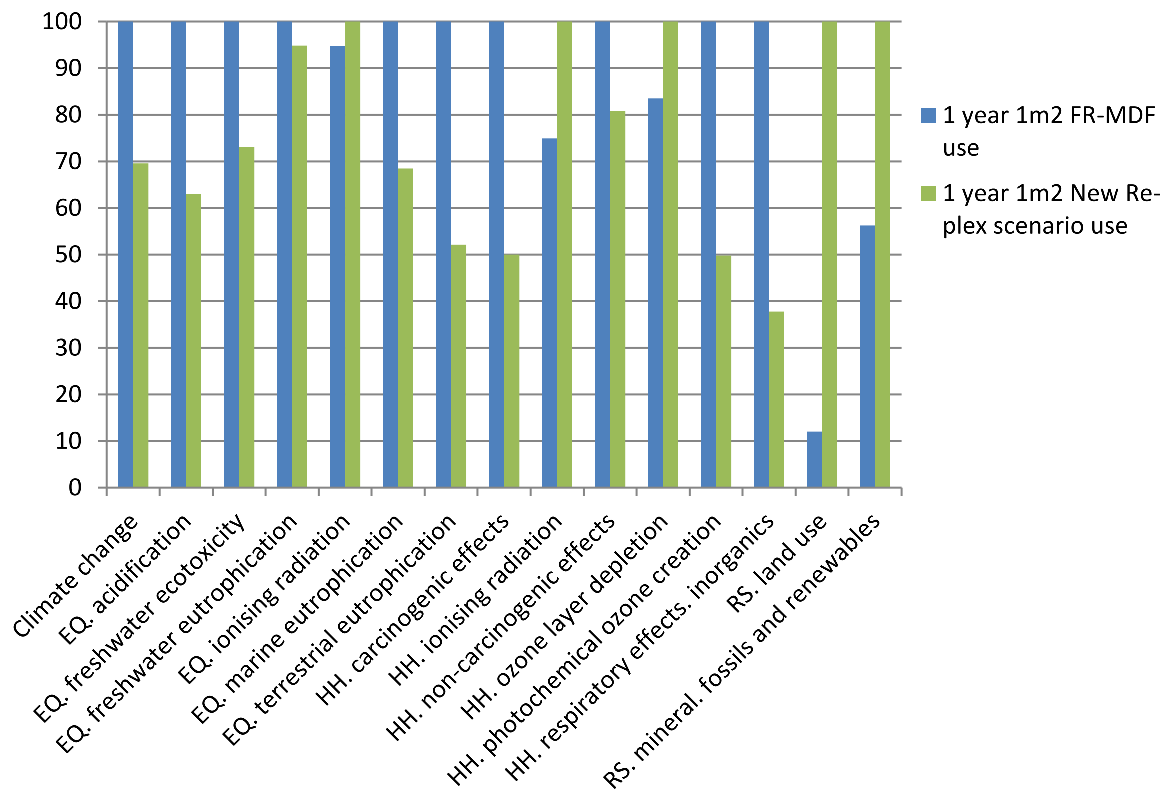


Figure 9: Characterisation results for the New Re-plex scenario (28% cellulose) and FR-MDF normalised to the highest impact of the two alternatives.

4.3.6 Single score indicator

A conclusion on which product (FR-MDF or the New Re-plex scenario) has a better environmental performance comes down to a value choice. The FR-MDF scores better on the five impact categories; EQ, ionizing radiation; HH, ionizing radiation; HH, ozone depletion; RS, land use; and RS, mineral, fossils and renewables. Especially the characterisation results RS, land use and RS, minerals fossils and renewables are important to consider. The characterisation results of FR-MDF are less than half of the new Re-plex production scenario in these impact categories.

The New Re-plex scenario scores better on the ten impact categories; Climate change; EQ, acidification; EQ, freshwater ecotoxicity; EQ, freshwater eutrophication; EQ, marine eutrophication; EQ, terrestrial eutrophication; HH, carcinogenic effects; HH, non-carcinogenic effects; HH, photochemical ozone creation; and HH, respiratory inorganics. Especially for the impact categories; EQ, terrestrial eutrophication; HH, carcinogenic effects; HH, photochemical ozone creation; and HH, respiratory effects, inorganics, the New Re-plex scenario has less than 50% of the characterisation results of FR-MDF.

To aid the decision making on which product performs better a single score indicator is used. It should be emphasized that this is based on a normative choice on how to weigh the impact categories relative to each other. There cannot be scientific consensus on the weighing factors to calculate a single environmental impact score for a product system (Pizzol et al., 2017).

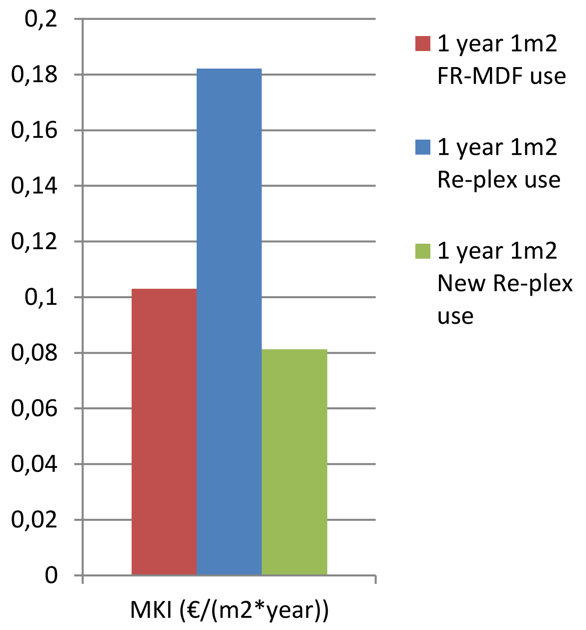


Figure 10: MKI single score results based on the CML-2001 baseline impact assessment family for FR-MDF, standard Re-plex and the New Re-plex scenario.

In the Dutch building sector the standard single score indicator is the Mileu-Kosten Indicator (MKI) (Stichting Nationale MilieuDatabase, 2020). This single score indicator uses the CML impact assessment family (Guinee, 2002). The impact categories are scored on their economic costs for society to mitigate the environmental impacts of the building material (Stichting Nationale MilieuDatabase, 2020). The MKI weighing factors for the CML baseline are given in the Appendix. The CML-2001 baseline characterisation results are calculated for FR-MDF, standard Re-plex and the New Re-plex scenario, these are also given in the Appendix. The sum of the weighed characterisation results gives the MKI single score (Figure 10).

From the MKI single score results it is clear that FR-MDF scores better than the standard Re-plex production, with €0.10/(m2*year) and €0.18/(m2*year) respectively. The New Re-plex scenario has a lower MKI single score €0.08/(m2*year) than FR-MDF. It should be stressed that this single score is based on a value choice, further considerations and discussions with policymakers on the importance of the different impact categories is required.

4.3.7 Sensitivity analysis

In the sensitivity analysis the robustness of the characterisation results to assumptions made in the inventory are tested. This shows to what extent the conclusions are based on the assumptions made and give a clearer view on what the boundary conditions are for the conclusions of the LCA to be valid. The sensitivity is analysed in two domains; Methodological assumptions and inventory assumptions.

Methodological assumptions

Methodological assumptions change the results of the inventory analysis and the classification of emissions. Subsequently these assumptions have an effect on the characterisation results and the conclusions drawn. A second impact assessment family is used to obtain characterisation results of the product systems. This enables a comparison between different impact categories based on which impact family is used. The impact assessment family that is used in the sensitivity analysis is the ReCiPe impact assessment family (Goedkoop, Heijungs, Huijbregts, Struijs, & van Zelm, 2009). This is the preferred method used by the STOWA and the National Institute for Public Health and the Environment (RIVM).

Next to the impact assessment family, the allocation method is subject of the sensitivity analysis. Energy based allocation is used in the standard model. Sludge waste treatment costs can differ significantly regionally and Kaumera prices are confidential and uncertain, therefore economic allocation was not the preferred allocation method. Nevertheless, in the sensitivity analysis economic allocation is used to determine the robustness of the results based on the type of allocation used.

The ReCiPe impact assessment family has 18 impact categories. Of these 18 impact categories, 6 are the same as for the ILCD impact assessment family. Namely: Climate change; Freshwater ecoxocitiy; Freshwater eutrophication; Marine eutrophication; Ionising radiation; and Ozone depletion. The characterisation results for the two product systems (FR-MDF, New Re-plex scenario) with the ReCiPe impact assessment family can be found in the Appendix.

The New Re-plex scenario scores better in the 14 impact categories: Agricultural land occupation; Climate change; Fossil depletion; Freshwater ecotoxicity; Freshwater eutrophication; Human toxicity; Marine ecotoxicity; Metal depletion; Natural land transformation; Particulate matter formation; Photochemical oxidant formation; Terrestrial acidification; Terrestrial ecotoxicity; and Urban land occupation. FR-MDF scores better in the 4 impact categories: Ionising radiation; Marine eutrophication; Ozone depletion; and Water depletion. Therefore the conclusion that in most impact categories the characterisation results for the New Re-plex scenario are lower than for FR-MDF is still valid.

For the six impact categories that are similar between the ReCiPe and ILCD impact assessment families, the ratios for the differences between the Re-plex and FR-MDF model can be found in Table 5. From this table it is clear that the impact results for both families have similar ratio's for the same impact categories, except for the impact category Marine eutrophication. Therefore the low Marine eutrophication impacts that are associated with Re-plex production based

Table 5: Ratio's between the characterisation results of FR-MDF and the New Re-plex scenario for six impact categories; Climate change; Freshwater ecotoxicity; Freshwater eutrophication; Marine Eutrophication; Ionising radiation; and Ozone layer depletion. The ratios are calculated for two impact assessment families, ILCD and ReCiPe.

Impact category	Ratio characterisation result New Re-plex/FR-MDF ILCD impact family	Ratio characterisation result New Re-plex/FR-MDF ReCiPe impact family
Climate change	0.696	0.697
Freshwater ecotoxicity	0.730	0.507
Freshwater eutrophication	0.948	0.890
Marine eutrophication	0.685	2.262
Ionising radiation	1.056	1.065
Ozone layer depletion	1.198	1.198

on the ILCD method is dependent on the impact assessment family used. There are some uncertainties in this impact category. Based on the specific impact site studied the environmental impact in marine eutrophication can differ up to two orders of magnitude (Henryson, Hansson, & Sundberg, 2018).

Next to these 6 same impact categories, the 2 ReCiPe impact categories; Agricultural land use; and natural land transformation are both lower for Re-plex. While the impact category; RS land use from the ILCD method is much higher for Re-plex. Therefore the conclusion that Re-plex results in large impacts in land use or agricultural land use and natural land transformation depends on the specific problem defined in the impact category and the characterisation model used.

Important to note is that the use of a different characterisation model to calculate the impact category results can have an influence on the conclusions. For Marine eutrophication and land use the conclusion that Re-plex performs better or worse than FR-MDF does not hold based on the comparison between the ILCD and ReCiPe impact assessment families.

For the economic allocation data on prices of the sludge waste treatment, Kaumera gel and electricity and heat in The Netherlands is collected (table 6). A comparison of the partitioning factors of the multifunctional processes to the functional flows based on energy and economic allocation are presented in table 6. The calculations of the economic allocation partitioning factors can be found in the Appendix.

From table 6 it is clear that the allocation factors are not very different between energy based and economic allocation. This is especially true for the separation of Kaumera, which has the same partitioning factor for energy- and economic based allocation. The economic allocation method

Table 6: The multifunctional flows and their energy content and revenue (A), and a comparison of the partitioning factors for energy based and economic allocation (B).

A:

Foreground process	Functional flow	Flow	Energy content	Revenue
Dissolve and separate Kaumera	Sludge (waste)	42,800 ton/year (4% DW)	-45MJ/kg DW	-€100/ton
	Na-bound Kaumera	9,800 ton/year (4% DW)	-45MJ/kg DW	€2.5/kg DW
Anaerobic digestion	Sludge residue (Waste)	37,300 ton/year (15% DW)	2.0MJ/kg DW	-€100/ton
	Biogas	357,390 m3	23.3MJ/m3	€0.2725/m3
Biogas incineration	Electricity	923,175 kWh	3,323,400 MJ	€0.095/kWh
	Heat	3,165,000 MJ	3,165,000 MJ	€0.097/kWh
Biomass residue incineration	Biomass residue (waste)	4,900 ton/year (23% DW)	8.0MJ/kg DW	-€100/ton
	Electricity	324,400 kWh	1,168,000 MJ	€0.095/kWh

B:

Foreground process	Functional flow	Energy based allocation	Economic allocation
Dissolve and separate Kaumera	Sludge (waste)	0.813	0.813
	Na-bound Kaumera	0.187	0.187
Anaerobic digestion	Sludge residue (Waste)	0.202	0.975
	Biogas	0.498	0.025
Biogas incineration	Electricity	0.512	0.751
	Heat	0.488	0.249
Biomass residue incineration	Biomass residue (waste)	0.886	0.941
	Electricity	0.114	0.059

is used to calculate the characterisation results, these can be found in the Appendix. As would be expected based on the similar partitioning factors for the multifunctional processes, the characterisation results between energy and economic allocation are almost the same. Therefore it can be concluded that the characterisation results are not influenced much by the methodological allocation choice. This strengthens the conclusions from the impact assessment.

Inventory assumptions

Certain assumptions made in the inventory analysis and scenario development are based on expectations of how Re-plex can be produced or perform in the future, as a product ready for market. However, since Re-plex production is still in pilot-stage, it is uncertain if these improvements can be obtained. To test the boundary conditions for the conclusions to hold, the most important assumptions of the inventory analysis are subjected to a sensitivity analysis. These assumptions are; the percentage Kaumera extraction from Nereda® sludge; the lifetime of Re-plex; and the energy efficiency of Re-plex production.

The extraction of Kaumera from Nereda® sludge is modelled to be 23% of the organic fraction after Visser et al. (2016). However, the extraction of Kaumera can be up to 35% of the organic fraction of the sludge (van de Knaap et al., 2019). The influence on the characterisation results of changing the Kaumera extraction to 35% in the inventory is calculated.

For the lifetime of Re-plex it is assumed that this is equal to the average lifetime of MDF plate, which is 32 years (Nakano et al., 2018). This is the average renovation time for building interiors, while the lifetime of MDF and can be up to 40 years. Due to the limited testing with Re-plex longevity and no market reference, the lifetime of Re-plex is assumed to equal to the lifetime of FR-MDF. Based on the limited testing Re-plex is expected to withstand degradation in dry conditions (S. Picken, personal communication, 14 June 2021), but Re-plex is not yet used in practice and has not been used for 32 years. Therefore in the sensitivity analysis the influence on the characterisation results for a lifetime of 20 years for Re-plex is calculated. In that case 1m2 of Re-plex would provide 20 years of Re-plex use instead of 32 years of Re-plex use.

Regarding the energy use of Re-plex production, it this is assumed that Re-plex production can obtain the same energy efficiency as MDF production. Since the current production process is on pilot scale it is assumed that this can be improved to be equal to energy use in MDF production on market scale. It is however unknown if these improvements can be obtained. It can also be the case that Re-plex production can be more efficient than MDF production. In the production of MDF, energy is required for the shredding and steaming of woodchips for mechanical pulping. This mechanical pulping is not needed for Re-plex production since it uses already pulped cellulose in the form of Recell® (Recell, n.d.). Taking these considerations into account, the sensitivity of the characterisation results to the energy usage is determined in 2 scenarios by increasing or decreasing the energy demand of the Re-plex production by 20% compared to the energy use of the New Re-plex scenario.

The characterisation results for the sensitivity analysis to the inventory assumptions are in table 7. In the scenario where the energy usage is decreased and increased by 20%, the resulting differences in characterisation results are small, about 5% of the characterisation results. When comparing these results to the characterisation results of FR-MDF we see that a change of 20% in energy use during Re-plex production does not influence the conclusions on which product performs better in each impact category. The conclusions on New Re-plex production hold as long as the energy use that can be obtained is in the same order of magnitude as MDF production.

For the lifetime of Re-plex this is different. The lifetime of Re-plex is linearly correlated with the functional unit (1 year 1m2 interior finishing material use). Therefore a decrease in lifetime incurs a same order of magnitude increase in the characterisation results. It can be seen that for a lifetime of 20 years instead of 32 years for Re-plex, the characterisation results for Re-plex almost double. Compared to FR-MDF it has a lower characterisation results in only 4 impact categories, with FR-MDF having lower characterisation results in 11 impact categories. The conclusions from the impact assessment are based on the assumption that a similar lifetime to MDF can be obtained for Re-plex. This shows the importance of being able to produce a product with a long lifetime. If a lifetime for Re-plex of 32 years cannot be obtained, the use of Re-plex as interior finishing material would not be a viable option. However, it is expected that this lifetime for Re-plex can be obtained (S. Picken, personal communication, 14 June 2021).

For a 35% separation of Kaumera from Nereda® sludge the inventory is changed. In this model less sludge residue is going to anaerobic digestion, producing less biogas. It thereby increases the external energy demand of the Kaumera extraction process. The upside however, is that more Kaumera gel is produced. From the characterisation results it is clear that increasing the Kaumera

Table 7: characterisation results for the sensitivity analysis to inventory assumptions, compared to the New Re-plex scenario use and FR-MDF.

Impact category	1 year of 1m2 FR-MDF use	1 year 1m2 New Re-plex scenario use	New Re-plex with 35% Kaumera extraction	New Re-plex with 20 years lifetime	New Re-plex with +20% energy requirement	New Re-plex with -20% energy requirement	Unit
Climate change	0.401	0.279	0.272	0.446	0.289	0.268	kg CO2-Eq
EQ. acidification	0.00241	0.00152	0.00147	0.00242	0.00154	0.00149	mol H+-Eq
EQ. freshwater ecotoxicity	3.45	2.52	2.4	4.03	2.58	2.46	CTUh.m3.yr
EQ. freshwater eutrophication	0.000116	0.00011	0.000103	0.000176	0.000114	0.000106	kg P-Eq
EQ. ionising radiation	1.07E-07	1.13E-07	1.05E-07	1.80E-07	1.16E-07	1.10E-07	mol N-Eq
EQ. marine eutrophication	0.000596	0.000408	0.000401	0.000654	0.000413	0.000404	kg N-Eq
EQ. terrestrial eutrophication	0.00645	0.00336	0.00333	0.00538	0.00344	0.00328	mol N-Eq
HH. carcinogenic effects	3.16E-08	1.58E-08	1.50E-08	2.52E-08	1.62E-08	1.54E-08	CTUh
HH. ionising radiation	0.0245	0.0327	0.0296	0.0523	0.034	0.0314	kg U235-Eq
HH. non-carcinogenic effects	1.46E-07	1.18E-07	1.11E-07	1.88E-07	1.19E-07	1.16E-07	CTUh
HH. ozone layer depletion	4.00E-08	4.79E-08	4.09E-08	7.66E-08	4.85E-08	4.73E-08	kg CFC-11-Eq
HH. photochemical ozone creation	0.00163	0.000811	0.00079	0.0013	0.000822	0.0008	kg ethylene-Eq
HH. respiratory effects. inorganics	0.000477	0.00018	0.000178	0.000289	0.000182	0.000179	kg PM2.5-Eq
RS. land use	3.54	29.4	29.4	47	29.4	29.4	kg Soil Organic Carbon
RS. mineral. fossils and renewables	1.53E-05	2.72E-05	2.44E-05	4.35E-05	2.72E-05	2.71E-05	kg Sb-Eq

separation from 23% to 35% results in a small decrease in impacts. The assumed percentage of Kaumera separation does not influence the conclusions from the impact assessment much. However, increasing the Kaumera separation poses an opportunity for a more efficient Re-plex production process. Important to note is that increasing the percentage of Kaumera separated increases the amount of fine particles in the Kaumera gel (van de Knaap et al., 2019). The influence of the different Kaumera composition on the cross-linking and stability of the Re-plex material should be studied first. If Kaumera from higher separation rates (35%) results in a decreased crosslinking function, and subsequently decreases the lifetime of Re-plex, it would be better to use the Kaumera gel from low separation rates (23%).

5. Discussion

In the following discussion the weaknesses and uncertainties in the LCA are discussed and directions for further research into Re-plex are given.

There are some notable discrepancies to the LCA. First, the choice of FR-MDF as alternative. The FR-MDF is one of the materials that Re-plex could replace. Other materials can also be a target for replacement depending on the function, such as high pressure laminate, glass fibre, poly-lactic acid or aluminium. A comparative LCA on these materials would be beneficial to determine which material Re-plex would be most suitable to replace from an environmental perspective. Second, capital goods (buildings, equipment) are out of scope in this LCA, similar to the model by Visser et al. (2016). The contribution of the capital goods to the environmental impact could be an important factor in a market scale Re-plex production process, while this is not included in this model. Care should be taken in the design of a market-scale Re-plex production process not to overlook the environmental impacts of capital goods. However, there is an economic drive to minimise the use of equipment and buildings, which in turn results in minimisation of the environmental impacts.

From the sensitivity analysis it could be concluded that the model is robust for the methodological choices of the impact assessment family and type of allocation used. Regarding the ILCD impact assessment family, the sensitivity analysis showed that the indicator results were robust for using another impact assessment family (ReCiPe). Only for the impact category called ''EQ, marine eutrophication'' the characterisation results were better for Re-plex in the ILCD impact family, while the results were better for FR-MDF in the ReCiPe impact assessment family. Therefore it is concluded that the results for this indicator can depend on the impact family used. For further studies care should be taken when interpreting the results of this indicator. The sensitivity analysis further showed that the choice for energy based allocation compared to economic allocation does not have a large influence on the LCA results.

The results of the LCA are very sensitive to the lifetime of Re-plex, since there is a linear correlation between the lifetime and the characterisation results. A point of focus should be to develop a Re-plex product with a lifetime comparable to MDF (32 years). The COMPRO team expects that a lifetime of 32 years is feasible for Re-plex (S. Picken, personal communication, 14 June 2021).

Further, some data gaps in the LCA model of Re-plex are present. The most important one is that in the model a background cellulose process produced from waste paper is used. Instead of Recell® cellulose, which is used in Re-plex production. The addition of more Recell® cellulose could help to reduce the impacts of Re-plex, but conclusions on cellulose use could not be drawn due to uncertainties. The Recell® is expected to have lower impacts than cellulose from waste paper (Y. Flapper, personal communication, 31 March 2021). However, since the recovery of Recell from wastewater requires more steps than sieving (e.g. sanitising, drying, palletisation), the environmental impacts should be further studied. Further research together with Recell® into the environmental performance is required to draw conclusions on the environmental performance of increasing the amount of cellulose in Re-plex.

Sorbitol is another compound used in Re-plex production. Unfortunately, there is no sorbitol production process present in the Ecoinvent database. The production of sorbitol is therefore substituted by glucose production, which is a precursor of sorbitol production. The production of sorbitol has higher environmental impacts than glucose production. Since sorbitol production requires the hydrogenation of glucose with the help of a catalyst. However, sorbitol is used in very small quantities in the Re-plex production process. The contribution of glucose to the environmental impact of Re-plex production is small as shown in the stage contribution analysis. Therefore it is expected that the substitution of sorbitol by glucose would not change the conclusions on the environmental performance of Re-plex.

The end-of-life process of Re-plex in the model is the treatment of waste wood with municipal incineration. However Re-plex could also be composted. This choice is not expected to influence the characterisation results much since the end-of-life process has a negligible contribution to the environmental impacts of Re-plex. As is shown in the stage contribution analysis. Further, the use of municipal incineration for municipal organic waste has lower environmental impacts than composting (Di Maria & Micale, 2015). It is expected that municipal incineration has a better environmental performance and would be the preferable end-of-life treatment for Re-plex.

The FR-MDF model has some data gaps as well. First of all, the use of furfuryl alcohol in the fire-retardant resin is not modelled. Unfortunately no production process for this chemical is present in the Ecoinvent database. The production of furfuryl alcohol is substituted by production of tetra-hydrofuran, which is produced by hydrogenation of furfuryl alcohol. Because furfuryl alcohol is used in small quantities this is not expected to have a large influence on the results of the LCA.

The end-of-life treatment of FR-MDF is split into two parts. The treatment of MDF waste with municipal incineration for the MDF plate, and the treatment of hazardous waste for the FR-resin. In reality this might not be possible due to the inseparability of the MDF and the resin. Therefore, a more realistic end-of-life model could assume the treatment of hazardous waste for the whole FR-MDF plate. This would result in higher environmental impacts for FR-MDF. Although, similar to Re-plex, the end-of-life process has only a small contribution to the environmental impacts of FR-MDF.

The STOWA report by Visser et al. (2016) and the LCA on Recell cellulose (Y. Flapper, personal communication, 31 March 2021; Remy et al., 2020) on the environmental performance of product recycling from wastewater both use a wastewater treatment perspective. They determined how recycling of products influences the environmental performance of the wastewater treatment process. Both studies use substitution to subtract the impacts of the recycled products from the impacts of wastewater treatment. These reports have no conclusions on the environmental performance of the recycled products compared to conventional products. In the LCA at hand a product perspective is used instead. The product recycled from wastewater (Re-plex) is compared to a conventional product (FR-MDF). Therefore no conclusions on the environmental performance of the wastewater treatment could be made. For further research, it would be good to have a holistic view on the recycling of products from wastewater. This can be done by combining the wastewater treatment perspective, and the product perspective in one LCA. The function of wastewater treatment and the function of a product, such as an interior finishing material should both be included in the LCA model by using system expansion. This model should be compared to a model including both the baseline wastewater treatment and the use of a conventional product such as FR-MDF. In this way conclusions can be drawn on the environmental impacts of the whole recycling process, from the wastewater treatment to the product use.

Interesting to discuss is that the citric acid in the Ecoinvent database is produced by a fermentation process, while the succinic acid and adipic acid are produced chemically. The chemically produced carboxylic acids have a much better environmental performance than biobased production of citric acid. This is expected to be due to the impacts from agriculture. For the fermentation of citric acid, a sugar source needs to be harvested from sugar crops such as corn, sugar cane or sugar beets. Agricultural processes result in high emissions for the use of agricultural machines, fertilizer and pesticides, as well as significant land use change. Although it can seem counterintuitive, petrochemical products can result in lower environmental impacts than biobased products. The preference for biobased products can be based on a value choice against the use of fossil resources, but it does not automatically reduce the environmental imapcts of a product system (Fiorentino, Ripa, & Ulgiati, 2017).

An important note is that the use of fossil oil for the production of chemical products does not need to be a problem. The alternatives for chemicals production; biobased production; or production from CO_2 and H_2 have their merits too. Biobased production of chemicals requires a lot of land, while chemical production from CO_2 and H_2 requires a lot of (green) energy production. Both these alternatives also result in significant emissions and use of resources. In the search for a sustainable world the use of oil for chemicals production should not be rejected up front, it should be carefully weighed against the alternatives. In this case, replacing the biobased citric acid by the chemically produced succinic acid results in a better environmental performance, since succinic acid performs better in all 15 impact categories of the ILCD impact family.

6. Conclusions

Based on this LCA study on Re-plex the following conclusions are highlighted:

- The better environmental performance of Re-plex compared to Fire Retardant MDF is highly dependent on the use of an alternative chemical that can successfully replace citric acid in the Re-plex production process. Succinic acid is able to replace citric acid and improve the environmental performance of Re-plex production.
- The better environmental performance of Re-plex compared to Fire Retardant MDF is dependent on the ability to improve the energy efficiency of the Re-plex production process. Since this study compares a mature process for MDF production with an innovative Re-plex production process, the latter one shows significant higher energy intensity. However, the energy intensity is expected to decrease over time when Re-plex production matures.
- The environmental performance of Re-plex is very sensitive to the lifetime of the plate material. For a better environmental performance of Re-plex compared to Fire Retardant MDF a lifetime of at least 32 years for Re-plex should be obtained. The COMPRO team assesses this lifetime for Re-plex to be feasible.
- When performing a comparative LCA, certain indicators can be sensitive to the impact assessment family used, and care should be taken when interpreting the result. In the LCA at hand the results for the indicator called ''Marine eutrophication'' depend on the use of the ILCD- or ReCiPe impact assessment family.
- Biobased chemicals do not always have a better environmental performance than petrochemicals, contrary to intuition. This is the case with biobased citric acid production having higher environmental impacts than petrochemical succinic acid production.

7. Recommendations and Outlook

Based on this thesis some recommendations to the COMPRO team and the engineers working on a Re-plex product are given.

The main recommendation is to experiment with the use of other Kaumera crosslinking components. The environmental impacts of citric acid used in standard Re-plex are very high compared to alternatives such as succinic acid. The engineers are advised to determine which materials can be used to replace citric acid and test which materials that gave a good environmental performance results in a good Re-plex product. The economic implications of replacing citric acid by succinic acid should not be insurmountable. The price of citric acid is about $0.6-0.8/kg (made-in-china.com, n.d.), while the price of succinic acid is about $1.8-1.9/kg (made-in-china.com, n.d.). Due to the lower molar weight of succinic acid, 9.6kg succinic acid is needed compared to 15.7kg citric acid per 100kg Re-plex. This results in a price of $11 for citric acid or $17.8 for succinic acid per 100kg Re-plex produced. It is important to stress that a better environmental performance of the Re-plex can add more value to the product, than the price difference between raw materials to be used. In this context it is important to note that the biobased production of citric acid has higher environmental impacts than the petrochemical production process of succinic acid. When assessing the best materials to use it is important to keep in mind that biobased production of materials does not necessarily have lower environmental impacts than petrochemical production of materials (Fiorentino et al., 2017).

Second, it is important to focus on realising the boundary conditions for improved environmental performance of Re-plex modelled in the LCA. This means that the energy efficiency of the Re-plex production process should be improved to be similar to MDF production, and that the lifetime of the Re-plex product should be 32 years, similar to the lifetime of an MDF plate.

A Third recommendation is to further study the environmental impacts of Recell® cellulose, preferably together with Recell®. Based on the LCA model in this thesis, it would not be advised to add more cellulose to Re-plex. However, this is due to the use of cellulose from waste paper in the LCA model instead of Recell®. Recell® is expected to result in lower environmental impacts. Validation of this fact would be beneficial for the robustness on the better environmental performance of Re-plex.

Last, it is recommended to interact with policymakers to promote the use of Re-plex. For this the results of the MKI single score indicator, in which the new Re-plex scenario scores better than FR-MDF can be used. It should however, be clear that the weighing of different impact categories to a single score is always based on normative choices (Pizzol et al., 2017). Policy makers should always be informed of this fact and given the overview of the characterisation results on all impact categories and the relevant knowledge to be able to discuss this.

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9. Glossary

In the glossary the technical terms in LCA are described. Although many technical terms are not used in this LCA, this guide can be used as reference for the technical terms for non-LCA experts. This glossary is copied from Consequential-LCA.org ('Glossary and Definitions', n.d.).

Activity: Making or doing something. Activities include human activities (production, consumption, and market activities, as well as accumulation of stocks) and environmental mechanisms, irrespective of their economic significance.

Allocation: In the context of LCA often used as jargon for co-product allocation (see this).

Attributional: A system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.

By-product (dependent product): Product output from a unit process that is not a determining product.

By-product technology model: See system expansion

Capital goods: The goods that are part of the capital expenditures of a facility. This includes the buildings, equipment and land occupation of a facility.

Co-product: Any of two or more product outputs coming from the same unit process or product system (ISO 14040, clause 3.10). Co-products may be determining products or by-products (dependent products).

Co-product allocation: Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. The partitioning results are as many partitioned systems as there are co-products in the original system. The sum of the partitioned systems equals the system before the partitioning.

Combined production: A production, where the relative amounts of co-products can be varied independently.

Consequential: A system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.

Constrained activity: Human activity that is limited in its ability to change its production volume in response to a change in demand for its product output.

Constrained market:: A market that is limited in its ability to provide the goods or services demanded.

Consumption mix: The output of a market activity.

Cross-price elasticity of demand: The change in demand for a product in response to a change in price for another product.

Demand: The costumer request for a product, reflecting a willingness to pay. The price of a market commodity is determined by the volume that can be produced at a marginal cost that equals the marginal demand.

Dependent product: See by-product (dependent product)

Determining product: Product output of an activity for which a change in demand will affect the production volume of the activity. Also sometimes called a reference product.

Determining property: A property of a product for which a difference in performance causes a change in production output.

Displaced treatment: A treatment that is reduced, replaced or substituted as a result of a change in supply or demand for the material for treatment.

Downstream (in the life cycle): Forward in the life cycle, towards the use and disposal of the product(s).

Environment: The surroundings in which an organisation operates. Can be sub-divided into the natural, social and economic environment.

Environmental exchanges: Environmental exchanges are environmental inputs to a product system (resources), environmental outputs from a product system (emissions to air, water and soil) as well as environmental relations of a product system, which are not directly connected to its inputs and outputs (e.g. land use, physical impacts, non-chemical aspects of occupational health, welfare of workers and domestic animals).

Environmental impact: A change to the environment, whether adverse or beneficial, resulting from an organisation's activities or products.

Exchange: Causal, directional relationship between two activities.

Functional unit: A quantified description of the performance of a product system, in terms of the obligatory product properties required by the market on which the product is traded.

Goods: Tangible products of an activity.

Human activity: Activity performed by humans, machines, or animals in human care. Can be classified in production activities, consumption activities, market activities, and accumulation of stocks). See also unit process.

Input/output analysis (IOA): Analysis of the product relationships (product inputs and outputs) between all activities of an economy, usually recorded in monetary units.

Input/output tables: An input-output table presents the supply (production) and the use (consumption) of goods and services (products) between all activities of an economy and the primary factors involved in that production, in a tabular format.

Joint production: A production, where the relative amounts of co-products cannot be varied independently (i.e. proportions are fixed).

Life cycle assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product (system) throughout its life cycle.

Life cycle inventory analysis (LCI): Phase of life cycle assessment involving the compilation and quantification of exchanges for a product throughout its life cycle.

Marginal consumer: The consumer that is least willing to pay the market price in a typical supply and demand equilibrium. This means that the marginal consumer is the consumer that stops purchasing if prices go up and increases purchasing when prices go down.

Marginal costs: The change in total costs resulting from a one unit change in output, i.e. the cost of producing an additional unit of a product.

Marginal production: See marginal supplier (long-term)

Marginal supplier (long-term): A supplier/producer that will change production capacity in response to a change in demand for a product (increase or decrease).

Market activity: A human activity representing a market for a specific product, mixing similar intermediate outputs from the supplying transforming activities and providing the resulting consumption mix to the transforming activities that consume this product as an input.

Market boundary: The spatial and temporal delimitation of a market, within which the price of a product is uniformly determined.

Market clearing price: A market clearing price is the price of a good or service at which quantity supplied is equal to the quantity demanded, also called the equilibrium price.

Market niche: A market niche is a smaller sub-category of a market segment, where a part of the customers consider only niche products substitutable.

Market segment: A market segment is defined in terms of clearly distinct requirements for obligatory product properties with a minimum of overlap to other segments. All products targeted for a segment are considered substitutable by the customers of this segment. Furthermore there should be low probability that a product targeted for another segment would be considered substitutable, implying that product substitution from segment to segment can be neglected.

Market-irrelevant product property: A market-irrelevant product property is a property that does not affect customer preferences and therefore does not affect product substitutability, but may influence the reference flow.

Material for treatment: By-product/waste that no other activity in the same geographical area has as its positive determining product, and which therefore cannot substitute a determining product as an input to an activity.

Near wastes: A recyclable material for treatment that is not fully utilised by recycling. When there is not enough demand an additional (marginal) supply of the material for treatment for recycling the rest will go to disposal (waste treatment).

Normalised market trend: Applied to a joint production, the trend for the market on which each joint product is sold, divided by (normalised to) the ratio of the joint product output relative to the output of all joint products from the joint production.

Obligatory product property: A property that a product must have in order to be considered by the customer as a relevant object for product substitution.

Positioning product property: A product property which is considered "nice to have" by the customer and which therefore positions the product more favourably with the customer relative to other products with the same obligatory product properties.

Price elasticity: The percentage change in quantity of supply or demand in response to a percentage change in price.

Product: Activity output with a positive either market or non-market value. Sub-divided in goods (tangible products) and services (intangible products).

Product life cycle: The production, use and final disposal of a product.

Product substitution: A replacement of one product or group of products with another product or group of products.

Product system: System of consecutive and interlinked unit processes, which models a product life cycle.

Rebound effect: The derived changes in production and consumption when the implementation of a decision liberates or binds a scarce production or consumption factor.

Recycling: A treatment activity with a by-product output that can displace determining products from other activities, thus reducing the demand for new (virgin) production of these determining products.

Reference flow: A reference flow is a quantified amount of product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit.

Reference product: See determining product

Revenue: The income from the sale of a product output (Revenue = price * amount)

Services: Products without mass, i.e. intangible products as opposed to goods.

Speciality production: An activity that requires a material for treatment as an input, but which is not a dedicated treatment activity (i.e. it has a positive determining product).

Substitution method: See system expansion

Supply: The quantity of a product which is provided by the manufacturers at a given price, and which is thus available to the customers.

System boundaries: The denominations of which entities are inside the system and which are outside.

System expansion: A procedure for eliminating by-products as activity outputs by including them instead as negative inputs, thereby including the additional functions related to the by-products and modelling the resulting changes (substitutions) in the product system, especially by including the reduction in supply of the same product from the marginal supplier to the market for the by-product.

Transforming activity: An activity that transforms inputs, so that the intermediate output of the activity is different from the intermediate inputs, as opposed to a market activity or accumulation of stock. Includes extraction, production, transport, consumption, and waste treatment and recycling activities.

Treatment activity: Transforming activity with a determining product with a negative sign, which means that the activity is supplying treatment or disposal of the determining product.

Treatment markets: Treatment markets are a specific kind of market activities that provide the services of treating or disposing of the wastes and by-products of other activities. The treatment markets operate on the negative determining products.

Unit process: The smallest human activity considered in a life cycle inventory analysis.

Upstream (in the life cycle): Backwards in the life cycle, towards the raw material extraction and production of the product(s).

Waste: There are many different definitions of waste, some of which have legal implications. In a neutral physical modelling, it is therefore preferable not to make a distinction between waste and by-products (see this). However, the definition of a product implies that an output of a human activity that has zero or negative market or non-market value (utility) is NOT a product and would therefore have to be classified as waste.

10. Appendix

Inventory foreground processes

The in- and outflows to all foreground processes of the LCA models for Re-plex and FR-MDF can be found in table A1 and table A2 respectively. For a complete overview of the inventory and the Ecoinvent background processes to which the flows are connected consult the supplementary excel file. The implementation in LCA software can be found in the supplementary CMLCA files.

Table A1: In- and outflows of all foreground processes of the FR-MDF composite model. The flows are goods unless it is indicated as a waste-flow.

Foreground process	Inflow	Amount	Unit	Outflow	Amount	Unit
Fire retardant production	Ethanol	0.02	kg	FR-resin	1	kg
	Furfuryl alcohol (substituted by tetra-hydrofuran)	0.3	kg			
	maleic anhydride	0.5	kg			
	ammonium phosphate	0.05	kg			
	water	0.13	kg			
MDF & FR-resin mixing	MDF	0.0120	m3	FR-MDF plate	1	m2
	FR-resin	0.4	kg			
MDF use & end-of-life	FR-MDF plate	1	m2	1 year of 1m2 FR-MDF use	32	m2*year
	transport	0.88	ton*km	Fibreboard waste **waste**	8.4	kg
				Hazardous waste **waste**	0.4	kg

Table A2: In- and outflows of all foreground processes of the Kaumera composite model. The flows are goods unless it is indicated as a waste-flow.

Foreground process	inflow	amount	unit	outflow	amount	unit
Thickening	wastewater sludge (raw influent WWTP) **waste**	7665000	ton/year	dewatered sludge (4% dry matter) **waste**	42800	ton/year
Dissolve and separate Kaumera	dewatered sludge **waste**	42800	ton/year	Na-bound kaumera 7% dry matter	32913	ton/year
	Sodium carbonate	214	ton/year	sludge residue **waste**	9887	ton/year
	heat	77	GJ			
	heat anaerobic digestion (AD)	2120	GJ			
	electricity AD	35000	kWh			
Precipitate Kaumera	Na-bound Kaumera	32913	ton/year	Kaumera gel	5629	ton/year
	hydrochoric acid	159	ton/year	acid centrate	27444	ton/year
	electricity AD	321389	kWh			
Drying of Kaumera	Kaumera gel	1	ton	Dry Kaumera	0.07	ton
	Heat	4.5291	gj			
Re-plex production	Kaumera gel	20.08	kg	Re-plex	100	kg
	cellulose	23.49	kg			
	glycerol	1.69	kg			
substituted by glucose	sorbitol	1.72	kg			
	citric acid	15.66	kg			
	kaumera dry	32.13	kg			
	electricity	142.59	kWh			
	transport	51.74	ton*km			
Re-plex use and end-of-life	Re-plex	9.6	kg	1 year Re-plex use	32	m2*year
	transport	0.96	ton*km	End-of-life Re-plex **waste**	9.6	kg
anaerobic digestion	Sludge residue **waste**	9887	ton/year	biogas	357390	m3
	Acid centrate	27444	ton/year	biomass residue wet **waste**	36975	ton
	heat AD	1045	GJ			
	electricity AD	1944.44	kWh			
biogas incineration	biogas	357390	m3	electricity from AD	923175	Kwh
				heat from AD	3165	gj
biomass residue water removal	biomass residue wet **waste**	36975	ton	biomass residue dry (23% dry weight) **waste**	4894	ton
	polyelectrolyte	10.5	ton			
	electricity AD	101389	kWh			
	Transport	1848775	Ton*km			
biomass residue incineration	biomass residue dry (23% dry weight) **waste**	4894	ton	electricity from AD	324444	kWh
	Lime	35	ton			

Assumptions inventory analysis

In the inventory analysis some assumptions are made on the amount of materials and energy used and the resulting outflows of the processes. These assumptions and their sources can be found in table A3.

Table A3: assumptions on Re-plex production and FR-MDF production for the inventory analysis.

Foreground process	Assumption	Source
Sludge thickening	Inflow wastewater 100.000 P.E.	(Visser et al., 2016)
	gravitational thickening	(Visser et al., 2016)
	to 4% dry weight	(Visser et al., 2016)
	Sludge treatment cost are €100/ton sludge	(P. Wilfert, personal communication, 27 May 2021)
dissolve and separate kaumera	kaumera separation on site	(R. Binnenveld, personal communication, 5 March 2021)
	sodium carbonate added 0.5% dry weight	(Visser et al., 2016)
	Na-bound Kaumera contains 23% of dry weight inflow	(Visser et al., 2016)
	The sludge residue contains 77% of dry weight inflow	Mass balances
	the sludge residue has 15% dry weight	(van de Knaap et al., 2019)
precipitate Kaumera	Kaumera is precipitated using hydrochloric acid	(van de Knaap et al., 2019; Visser et al., 2016)
	10L 36% Hydrochloric acid is added per m3 inflow	(Visser et al., 2016)
	Kaumera gel has 7% dry weight	(R. Binnenveld, personal communication, 5 March 2021)
	acid centrate contains the rest of the stream	mass balances
	Price Kaumera is €2.5/kg DW	(P. Wilfert, personal communication, 27 May 2021)
drying of kaumera	average spray drying energy use assumed	(Baker & McKenzie, 2007)
Re-plex production	Recipe	(P. Mooij, personal communication, 24 February 2021)
	electricity usage	(M. Lepelaar & I. Jansen, personal communication, 24 March 2021)
	Transport from Zuthpen to Amsterdam	(P. Mooij, personal communication, 24 February 2021)
Re-plex usage	dimensions and density	(P. Mooij, personal communication, 24 February 2021)
	100km transport to end-user	None
	End-of-life waste wood	None
	32 years lifetime	(S. Picken, personal communication, 14 June 2021)
Anaerobic digestion	inflow is sludge residue + acid centrate	(van de Knaap et al., 2019)

	anaerbic digestor is situated on WWTP	(P. Kehrein, personal communication, 5 May 2021)
	OD degradation is 46% (due to better digestiability through acid and base addition)	(Visser et al., 2016)
	biogas production is 0.76nm3/kg OD degradation	(Visser et al., 2016)
	biogas contains 65% methane, 35% CO_2	(Visser et al., 2016)
	sludge residue contains 54% of the OD inflow	Mass balances
	1% biogas slip (leakage to environment)	(Vogt, 2008; Woess-Gallasch et al., 2010)
Biogas incineration	efficiency of electricity production is 38%	(Visser et al., 2016)
	efficiency of heat production is 40%	(Visser et al., 2016)
	Complete incineration to CO_2	none
	Price of biogas is assumed to be similar to natural gas €0.2725/m3.	(CBS, 2021)
	Price of heat (assumed to be produced by natural gas incineration) is €0.097/kWh	(*Natural Gas Prices*, 2020)
	Price of electricity is assumed to be €0.095/kWh	(*Netherlands Electricity Prices*, 2020)
biomass residue drying	residue is transported 50km to incineration facility	(Visser et al., 2016)
	mechanically dewatered with added polyelectolyte	(Visser et al., 2016)
	dewatered to 23% dry weight	(Visser et al., 2016)
	Higher heating value of 2.03MJ/kg sludge (15% dry weight)	(Sahu, Sahu, Chakradhari, & Patel, 2016) corrected for heating and evaporation of water
Biomas residue incineration	Higher heating value of 8.04MJ/kg sludge (23% DW)	(Sahu et al., 2016) corrected for heating and evaporation of water
	Dry weight has molecular formula $CH_{1.77}O_{0.49}N_{0.24}$	(Grosz & Stephanopoulos, 1983)
	Complete incineration to CO_2	none
MDF production	40% Resin added to MDF on weight basis	(Kong et al., 2018)
	400g/m2 Resin added	(Ma et al., 2013)
FR-Resin production	maleic anhydride-ammonium phosphate based resin	(Kong et al., 2018)
MDF installation	dimensions and density	(Allesovermdf.nl, n.d.)
	100km transport to end-user	None
	End-of-life treatment waste fibreplate for MDF and treatment of hazardous waste for FR-resin	None
	lifetime 32 years	(Nakano et al., 2018)

Calculations inventory analysis

For the inventory analysis some calculations on energy usage and emissions of processes are performed. These calculations are described here per foreground process.

Drying of Kaumera

It is assumed that the average spray drying energy use is 4.87GJ/ton water heat energy (Baker & McKenzie, 2005).

The dry weight of Kaumera is 7% (Robbert Binnenveld, Chaincraft, Personal Communication).

Energy use for drying 1 ton of Kaumera gel is calculated: $4.87GJ/Ton\ water\ * \frac{1\ Ton\ Kaumera\ gel}{0.93\ Ton\ water\ /\ Ton\ Kaumera\ gel} = 5.237GJ\ /\ Ton\ Kaumera$

The amount of dry Kaumera that the drying of 1 ton Kaumera gel produces is calculated:

$$1\ Ton\ Kaumera\ gel * 0.07\ Ton\ dry\ Kaumera/\ Ton\ Kaumera\ gel\ = 0.07\ Ton\ dry\ Kaumera$$

Anaerobic digestion of sludge residue

The emission of biogas is modelled to be 1% of the total biogas production in anaerobic digestion similar to Pucker et al. (2013). total biogas production of 361000m3/year. With 65% methane in biogas and a density of 0.648kg/m3 methane, the methane emission is calculated:

$$361000m3\ biogas/year * 0.01\ biogas\ leakage * 0.65methane/biogas * 0.648kg/m3\ methane\ = 2340kg\ methane/year$$

With 35% CO2 in the biogas and a density of 1.784kg/m3 CO2 the CO2 emission is calculated:

$$361000m3\ biogas/year * 0.01\ biogas\ leakage * 0.35\ CO2/biogas\ * 1.784kg/m3\ CO2 = 2254kg\ CO2/year$$

Biogas incineration

The biogas is assumed to be completely incineration to CO2. 35% of the biogas is emitted as CO2, 65% is methane which is incinerated to CO2. The molar mass of methane is 16 g/mole, the molar mass of CO2 is 48 g/mole. The CO2 production for 0.648kg/ m3 of methane incinerated is calculated to be:

$$0.648kg\ methane * \frac{48\frac{g}{mole}CO2}{16\frac{g}{mole}methane} = 1944kg\ CO2$$

With a biogas incineration of 357390m3/year, this results in the following total CO2 emission:

$$357390m3 * 0.65\ methane * 1.944kg\ CO2/m3\ methane + 357390m3 * 0.35\ CO2 * 1.784kg\ CO2/m3 = 674752kg\ CO2$$

Sludge residue incineration

For the sludge incineration it is assumed that the dry weight has a comparable composition to biomass: $CH_{1.77}O_{0.49}N_{0.24}$. This results in a molar mass of 25g/mole. Further, complete incineration to CO2 is assumed. 4894 ton/year biomass residue is incinerated, this has 23% dry weight. These assumptions result in the following calculation for CO2 emissions:

$$4894ton\ sludge * 0.23\ biomass * \frac{\frac{48g}{mole} CO2}{\frac{25g}{mole} biomass} = 2{,}161{,}190kg\ CO2$$

Re-plex production

The data on electricity use of Re-plex production is obtained from Mark Lepelaar, NPSP (personal communication). The Re-plex production uses an oven to dry the mixed Re-plex dough for 3.5h, this oven uses 1.5A at 400V. After drying the Re-plex plates are pressed at 10 Bar for 15 minutes at 145°C and 30 minutes at 160°C, the press uses 5.5A at 145°C and 6A at 160°C. One plate of Re-plex weighs 0.45kg. Under current production conditions, a maximum of 6 plates can be produced at the same time.

The electricity requirements per batch are calculated:

$$3.5h/batch * 1.5A * 400V + 0.25h/batch * 5.5A * 400V + 0.5h/batch * 6A * 400V = 3.85\ kWh/batch$$

From this data the electricity requirements for the production of 100kg Re-plex is calculated:

$$\frac{100kg\ Re-plex}{0.45kg\ Re-plex\ /\ plate * 6\ plates\ /\ batch} * 3.85kWh/batch\ = 142.6kWh/100kg\ Re-plex$$

The transport for Re-plex production is determined by calculating the distance from the production locations to Amsterdam for the sourced materials. For background processes which have transport included this is assumed to be sufficient. Kaumera gel is transported from the production location in Zutphen to Amsterdam (108km, Google maps), where part of the Kaumera gel is dried. The amount of Kaumera gel transported per 100kg Re-plex is:

$$20.08kg\ Kaumera\ gel + \frac{32.13dry\ Kaumera}{0.07\ Dry\ Kaumera/Kaumera\ gel} = 479.08kg\ Kaumera\ gel$$

This amount of Kaumera gel is transported over 108km, resulting in the following transport requirement:

$$479.08kg\ Kaumera\ gel * 108km = 51.74ton * km$$

Re-plex use

The Re-plex is used in 1 square meter according to the functional unit. The thickness of the Re-plex plates is 8mm and the density is 1.2g/cm3(P. Mooij, personal communication, 24 February 2021). The resulting weight of a square meter of Re-plex is:

$$1m2\ Re-plex * 0.008m\ thickness * 1.2g/cm3\ Re-plex = 9.6kg\ Re-plex$$

The transport needed for Re-plex use is assumed to be on average 100km from the production location in Amsterdam. The transport needed is calculated:

$$100km * 9.6kg/m2\ Re-plex = 0.96Ton * km/m2\ Re-plex$$

MDF-production

The volume and weight of an MDF plate is calculated based on its average dimensions. The background process for MDF production uses the volume of MDF. The MDF is 1m2 according to the functional unit, the thickness is 12mm with a density of 700kg/m3 (allesovermdf.nl, n.d.). This result in the following volume for a MDF plate:

$$1m2\ MDF * 0.012m\ thickness = 0.012m3\ MDF$$

And the following weight:

$$0.012m3\ MDF * 700kg/m3\ MDF\ = 8.4kg\ MDF$$

The amount of maleic anhydride-based FR-resin used is assumed to be 0.4 kg per m2 plate material (Zhang, Hu, & Brown, 2014). This results in the following weight for the total FR-MDF plate:

$$8.4kg\ MDF/m2 + 0.4kg\ FR - resin\ = 8.8\ kg\ FR - MDF/m2$$

MDF-use

The transport needed for MDF use is assumed to be on average 100km from the production location to the instalment location. The transport needed is calculated:

$$100km * 8.8kg/m2\ MDF = 0.088\ Ton * km/m2\ MDF$$

The emission of formaldehyde during the use phase of the MDF has been calculated based on the log time model by Nakano et al. (2018). It is assumed that European MDF has the Japanese F*** rating for formaldehyde emissions (0.07mg/m3). This correspond with a rating under the European formaldehyde emission limit (0.10mg/m3) (Ruffing, 2011). The emission formula from Nakano et al. (2018) for F*** rated MDF in kg/m2/h is:

$$EF(t) = -0.000731\ln(t) + 0.0125$$

The integral of this formula over the lifetime of the MDF results in the total formaldehyde emissions over the lifetime of MDF. The first week after production is assumed to be emitted during the production and transport of the plate, thus the lifetime start at 168h. Since the lifetime of MDF is assumed to be 10 year, the resulting lifetime is 87660h. The resulting integral is:

$$\int_{168}^{87660} (-0.000731 \log(t) + 0.0125)\, dt =$$

$$428.933\ \text{mg/m}^2 \text{ (milligrams per square meter)}$$

Thus the formaldehyde emission over the 10 year lifetime of the MDF is 4.289E-4 kg/m2.

Allocation calculations

Below the calculation of the partitioning factors is described for the four multifunctional processes. Both energy-based and economic partitioning factors are calculated.

Dissolve and separate Kaumera

The allocation between the waste treatment of wastewater sludge and the production of Na-bound Kaumera is based on energy content of both flows. The Na-bound Kaumera flow contains 23% of the dry matter of the whole stream (Visser et al., 2016). It is assumed that the dry matter of both streams are similar enough to have the same energy content per kg. So for every Joule in the inflow, 0.23 Joule flows out in the Na-bound Kaumera stream. It results in the following partitioning:

$$\frac{1\,Joule/wastewater\ sludge}{1\,Joule/wastewater\ sludge\ +0.23\,Joule/Na-bound\ Kaumera}=0.8130$$

The energy based allocation to the wastewater sludge treatment is 0.8130. The allocation to the Na-bound Kaumera is subsequently 0.1870.

For economic allocation the prices used for the Kaumera gel produced is €2.5/kg dry Kaumera. The revenue is calculated for the amount of Kaumera gel produced after both separation and precipitation. The costs of sludge treatment is €100/ton of wet sludge. The sludge treatment is calculated for the gravitationally thickened Nereda® sludge. This results in the following partitioning:

$$\frac{394\ ton\ dry\ Kaumera * €2500/\ ton\ dry\ Kaumera}{394\ ton\ dry\ Kaumera * €2500/\ ton\ dry\ Kaumera + 42800\ ton\ sludge * €100/ton\ sludge}=0.1871$$

The economic allocation to the Kaumera production is 0.1871. The allocation to the wastewater sludge treatment is subsequently 0.8129.

Anaerobic digestion of sludge residue

The anaerobic digestion of sludge performs both functions of sludge residue treatment and biogas production. Biogas production is 0.35m3/kg dry weight (Visser et al., 2016). 1% of the biogas is assumed to leak from the installation. The higher heating values (HHV) of sludge residue and biogas are 16MJ/kg and 26.3MJ/m3 respectively (Fuel Gases Heating Values, n.d.; Huang, Chiueh, & Lo, 2021). The density of biogas is 0.993kg/m3 (Gases - Densities, n.d.). The HHV of sludge residue needs to be corrected for the energy required for the evaporation of water from the stream, this is 2.6MJ/ton water (Caduff, 2007). The sludge residue has a dry weight of 15% (van de Knaap et al., 2019). This results in the following calculation for energy in the sludge residue and the biogas:

$$\frac{1kg\ dw\ sludge\ residue * 16MJ/kg\ dw\ -0.85kg\ water\ /0.15\ kg\ dw\ sludge\ * 2.6kJ/kg\ water}{0.35m3\frac{biogas}{kg}dw * 0.99\ * 26.3MJ/m3\ biogas + (1kg\ dw\ sludge\ residue * 16MJ/kg\ dw\ -0.85kg\ water\ /0.15\ kg\ dw\ sludge\ * 2.6kJ/kg\ water)}$$
$$=0.2019$$

The energy based allocation to the sludge residue treatment is 0.2019. The allocation to the biogas production is subsequently 0.7981.

For the economic allocation the costs for sludge treatment are €100/ton wet sludge. The sludge inflow into the anaerobic digestion is 37330 ton/year. For the biogas produced the natural gas price in The Netherlands of €0.27254/m3 gas is used. The biogas production is 357390m3/year. This results in the following allocation:

$$\frac{37330\ ton\ sludge * €100/ton\ sludge}{37330\ ton\ sludge * €100/ton\ sludge + 357390m3\ biogas * €0.27254/m3\ gas} = 0.9746$$

The economic allocation to the sludge residue is 0.9746. Subsequently the allocation to the biogas production is 0.0254.

Biogas incineration

The incineration of biogas produces both heat (3165 GJ/year) and electricity (923175 kWh/year). This results in the following calculation for energy based partitioning:

$$\frac{3165GJ\ heat/year}{3165GJ\ heat/year\ + 923175kWh/year\ * 0.036GJ/kWh} = 0.4878$$

The energy based allocation to the heat production in biogas incineration is 0.4878. The allocation to the electricity production in biogas incineration is thus 0.5122.

The economic allocation of the biogas incineration is calculated with the price of heat generated with natural gas, €0.0092/MJ. The electricity price for companies in The Netherlands is €0.095/kWh. This results in the following allocation:

$$\frac{923175kWh\ electricity * €0.095/kWh}{923175kWh\ electricity * €0.095/kWh\ + 3165030MJ\ heat\ * €0.0092/MJ} = 0.7506$$

The economic allocation to the electricity production from biogas incineration is 0.7506. Subsequently the allocation to the heat production is 0.2494.

Biomass residue incineration

The total dry weight in the sludge residue is 77% of the total inflow of dry mass from the wastewater sludge (23% is in the Na-bound Kaumera). The total inflow of wastewater sludge is 42800ton/year with 4% dry mass. The biomass residue has the same dry weight as the sludge residue except for the biogas that has been emitted during anaerobic digestion. This results in the following flow of dry weight per year:

$$42800ton\ sludge/year\ * 0.04ton\ dw/ton\ sludge * 0.77\ - 361000m3\ biogas/year * 0.993kg/m3\ biogas\ = 963352kg\ dw/year$$

The HHV of sludge residue (16MJ/kg dw) needs to be corrected for the energy required for the evaporation of water from the stream, this is 2.6MJ/ton water (Caduff, 2007). The biomass residue after mechanical dewatering has a dry weight of 23% (Visser et al., 2016).

The electricity production per year in residue incineration is 324444kWh. This results in the following calculation for energy based partitioning:

$$\frac{324444kWh * 3.6MJ/kWh}{324444kWh * 3.6MJ/kWh\ + (963352kg\ dw * 16MJ/kg\ dw - 0.77kg\ water\ /0.23\ kg\ dw\ sludge\ * 2.6kJ/kg\ water)} = 0.2119$$

The energy based allocation to the electricity production in sludge residue incineration is 0.2119. The allocation to the biomass residue treatment is subsequently 0.7881.

For the economic allocation the cost used for sludge incineration is €100/ton wet sludge. The amount of sludge that is incinerated is 4894 ton sludge. For the electricity production a price of €0.095/kWh is used. The amount of electricity that is generated is 324444kWh. This results in the following allocation:

$$\frac{324444kWh\ electricity * €0.095/kWh}{324444kWh\ electricity * €0.095/kWh + 4894\ ton\ sludge\ residue * €100/ton\ sludge} = 0.0592$$

The economic allocation to the electricity production in sludge residue incineration is 0.05925. Subsequently the allocation to the sludge residue treatment is 0.9408.

Impact assessment results

The characterisation results for the standard Re-plex model and the FR-MDF scenarios can be found in table A4. The normalised results to the 2010 EU-27 domestic emissions (Benini et al., 2014) can be found in table A5. The characterisation results for the stage contribution analysis can be found in table A6. The characterisation results for the scenario development of Re-plex can be found in table A7 and table A8.

Table A4: ILCD impact family characterisation results for Re-plex production and use and FR-MDF production and use.

Impact category	1 year 1m2 Re-plex use	1 year 1m2 FR-MDF use	Unit
Climate change, GWP 100a	0.69019	0.401	kg CO2-Eq
Ecosystem quality, freshwater and terrestrial acidification	0.004041	0.002415	mol H+-Eq
Ecosystem quality, freshwater ecotoxicity	5.3082	3.4529	CTUh.m3.yr
Ecosystem quality, freshwater eutrophication	0.000267	0.000116	kg P-Eq
Ecosystem quality, ionising radiation	1.78E-07	1.07E-07	mol N-Eq
Ecosystem quality, marine eutrophication	0.001043	0.000596	kg N-Eq
Ecosystem quality, terrestrial eutrophication	0.008851	0.006451	mol N-Eq
Human health, carcinogenic effects	3.43E-08	3.16E-08	CTUh
Human health, ionising radiation	0.06171	0.024531	kg U235-Eq
Human health, non-carcinogenic effects	2.10E-07	1.46E-07	CTUh
Human health, ozone layer depletion	7.93E-08	4.00E-08	kg CFC-11-Eq
Human health, photochemical ozone creation	0.001621	0.001626	kg ethylene-Eq
Human health, respiratory effects, inorganics	0.000445	0.000477	kg PM2.5-Eq
Resources, land use	118.42	3.5404	kg Soil Organic Carbon
Resources, mineral, fossils and renewables	7.03E-05	1.53E-05	kg Sb-Eq

Table A5: Normalisation results for the standard Re-plex model and the FR-MDF model. The characterisation results are normalised to the EU-27 domestic production in 2010.

Impact category	1 year 1m2 replex use normalised	1 year 1m2 FR-MDF use normalised	Unit	Total domestic production EU-27 2010	Unit
Climate change	1.52E-13	8.72E-14	year	4.60E+12	kg CO2-Eq
EQ. acidification	1.74E-13	1.02E-13	year	2.36E+10	mol H+-Eq
EQ. freshwater ecotoxicity	1.25E-12	7.92E-13	year	4.36E+12	CTUh.m3.yr
EQ. freshwater eutrophication	3.66E-13	1.57E-13	year	7.41E+08	kg P-Eq
EQ. ionising radiation			year		mol N-Eq
EQ. marine eutrophication	1.25E-13	7.06E-14	year	8.44E+09	kg N-Eq
EQ. terrestrial eutrophication	1.03E-13	7.36E-14	year	8.76E+10	mol N-Eq
HH. carcinogenic effects	1.91E-12	1.72E-12	year	1.84E+04	CTUh
HH. ionising radiation	1.11E-13	4.35E-14	year	5.64E+11	kg U235-Eq
HH. non-carcinogenic effects	8.12E-13	5.49E-13	year	2.66E+05	CTUh
HH. ozone layer depletion	7.42E-15	3.70E-15	year	1.08E+07	kg CFC-11-Eq
HH. photochemical ozone creation	1.05E-13	1.03E-13	year	1.58E+10	kg ethylene-Eq
HH. respiratory effects. inorganics	2.41E-13	2.51E-13	year	1.90E+09	kg PM2.5-Eq
RS. land use	3.17E-12	9.47E-14	year	3.74E+13	kg Soil Organic Carbon
RS. mineral. fossils and renewables	1.44E-12	3.04E-13	year	5.03E+07	kg Sb-Eq

Table A6: ILCD impact assessment results of the stage contribution analysis of 100kg Re-plex production and end-of-life. With the stages; Cellulose production; Kaumera production; Citric acid production; Glucose production; Glycerine production; Energy usage; Re-plex transport; and Re-plex end-of-life.

Impact category	Kaumera production & transport	Cellulose production	Citric acid production	Glucose production	Glycerine production	Electricity usage	Re-plex transport to building	Re-plex end-of-life
Climate change	1.724	1.6093	9.8765	0.22985	0.56161	8.0711	0.12564	0.15586
EQ. acidification	0.010351	0.013371	0.081543	0.002194	0.003762	0.018317	0.000387	0.001601
EQ. freshwater ecotoxicity	19.491	24.974	72.384	2.5661	3.3411	46.254	0.74963	4.465
EQ. freshwater eutrophication	0.000848	0.000704	0.003476	0.000104	0.000123	0.003332	1.05E-05	6.07E-05
EQ. ionising radiation	1.06E-06	5.56E-07	1.73E-06	7.12E-08	8.93E-08	2.2E-06	6.03E-08	2.76E-08
EQ. marine eutrophication	0.001658	0.002661	0.019936	0.001982	0.003033	0.003652	7.47E-05	0.000804
EQ. terrestrial eutrophication	0.018027	0.027789	0.15413	0.007405	0.013438	0.058557	0.000823	0.007717
HH. carcinogenic effects	1.19E-07	1.33E-07	4.95E-07	1.8E-08	2.08E-08	3.07E-07	4.04E-09	2.38E-08
HH. ionising radiation	0.34329	0.13491	0.45487	0.020601	0.024926	1.0046	0.00971	0.005168
HH. non-carcinogenic effects	9.92E-07	9.24E-07	2.81E-06	2.91E-07	4.2E-07	1.17E-06	3.04E-08	2.63E-07
HH. ozone layer depletion	7.51E-07	1.46E-07	1.12E-06	1.53E-08	6.2E-08	4.31E-07	2.34E-08	1.4E-08
HH. photochemical ozone creation	0.00471	0.007809	0.028175	0.000658	0.001374	0.008286	0.000311	0.001903
HH. respiratory effects. inorganics	0.001026	0.002146	0.009908	0.000166	0.0003	0.000803	6.14E-05	0.000194
RS. land use	5.9963	16.023	2898.2	398.23	456.91	8.3289	0.66341	0.4933
RS. mineral. fossils and renewables	0.000337	0.000361	0.001503	2.05E-05	4.17E-05	3.52E-05	9.38E-06	3.88E-06

Table A7: ILCD impact family characterisation results for Re-plex production scenarios with succinic acid, improved energy efficiency and reduced Kaumera transport.

Impact category (unit)	1 year 1m2 Re-plex use (succinic acid)	1 year 1m2 Re-plex use (improved energy efficiency)	1 year 1m2 Re-plex use (reduced Kaumera transport)	1 year 1m2 FR-MDF use
Climate change, GWP 100a (kg CO2-Eq)	0.514	0.526	0.724	0.401
Ecosystem quality, freshwater and terrestrial acidification (mol H+-Eq)	0.00207	0.00388	0.00431	0.002415
Ecosystem quality, freshwater ecotoxicity (CTUh.m3.yr)	3.88	4.54	5.67	3.4529
Ecosystem quality, freshwater eutrophication (kg P-Eq)	0.000201	0.000198	0.000286	0.000116
Ecosystem quality, ionising radiation (mol N-Eq)	1.81E-07	1.34E-07	1.83E-07	1.07E-07
Ecosystem quality, marine eutrophication (kg N-Eq)	0.000518	0.00102	0.00111	0.000596
Ecosystem quality, terrestrial eutrophication (mol N-Eq)	0.00506	0.00799	0.00943	0.006451
Human health, carcinogenic effects (CTUh)	2.46E-08	2.90E-08	3.66E-08	3.16E-08
Human health, ionising radiation (kg U235-Eq)	0.0611	0.0395	0.0649	0.024531
Human health, non-carcinogenic effects (CTUh)	1.54E-07	1.97E-07	2.24E-07	1.46E-07
Human health, ozone layer depletion (kg CFC-11-Eq)	6.30E-08	7.35E-08	8.15E-08	4.00E-08
Human health, photochemical ozone creation (kg ethylene-Eq)	0.00108	0.00154	0.00172	0.001626
Human health, respiratory effects, inorganics (kg PM2.5-Eq)	0.000211	0.000464	0.000476	0.000477
Resources, land use (kg Soil Organic Carbon)	29.7	126	126	3.5404
Resources, mineral, fossils and renewables (kg Sb-Eq)	2.96E-05	7.59E-05	7.54E-05	1.53E-05

Table A8: ILCD impact family characterisation results for the new Re-plex production scenario with 28% cellulose or 40% cellulose.

Impact category	1 year 1m2 New Re-plex use (28% cellulose)	1 year 1m2 New Re-plex use (40% cellulose)	1 year 1m2 FR-MDF use	Unit
Climate change, GWP 100a	0.279	0.287	0.401	kg CO2-Eq
Ecosystem quality, freshwater and terrestrial acidification	0.00152	0.00162	0.002415	mol H+-Eq
Ecosystem quality, freshwater ecotoxicity	2.52	2.75	3.4529	CTUh.m3.yr
Ecosystem quality, freshwater eutrophication	0.00011	0.000114	0.000116	kg P-Eq
Ecosystem quality, ionising radiation	1.13E-07	1.14E-07	1.07E-07	mol N-Eq
Ecosystem quality, marine eutrophication	0.000408	0.000422	0.000596	kg N-Eq
Ecosystem quality, terrestrial eutrophication	0.00336	0.00358	0.006451	mol N-Eq
Human health, carcinogenic effects	1.58E-08	1.68E-08	3.16E-08	CTUh
Human health, ionising radiation	0.0327	0.0327	0.024531	kg U235-Eq
Human health, non-carcinogenic effects	1.18E-07	1.24E-07	1.46E-07	CTUh
Human health, ozone layer depletion	4.79E-08	4.67E-08	4.00E-08	kg CFC-11-Eq
Human health, photochemical ozone creation	0.000811	0.000878	0.001626	kg ethylene-Eq
Human health, respiratory effects, inorganics	0.00018	0.000201	0.000477	kg PM2.5-Eq
Resources, land use	29.4	27.3	3.5404	kg Soil Organic Carbon
Resources, mineral, fossils and renewables	2.72E-05	3.07E-05	1.53E-05	kg Sb-Eq

Scenario development calculations

For the development of the scenarios it is calculated how much carboxylic acids are needed for the crosslinking function. For the characterisation results of the three carboxylic acids see table A9. The calculation of the improved energy efficiency of Re-plex production and the reduced transport of Kaumera is described below.

Table A9: Comparison and charactarisation results of three carboxylic acids; citric acid; Succinic acid; and Adipic acid. Comparison of the amount of carboxylic acid needed for the same stoichiometric amount (A). ILCD characterisation results for the three carboxylic aicds (B).

A:

	Citric acid	Succinic acid	Adipic acid	unit
molar weight	192.123	118.088	146.142	g/mol
bonds used	2	2	2	mol
amount of bonds total	163	163	163	mol
amount added	15.66	9.63	11.91	kg

B:

Impact category	Citric acid 15.66kg	Succinic acid 9.63kg	Adipic acid 11.91kg	Unit
Climate change	103	31.4	177	kg CO2-Eq
EQ. acidification	0.849	0.128	0.401	mol H+-Eq
EQ. freshwater ecotoxicity	754	157	293	CTUh.m3.yr
EQ. freshwater eutrophication	0.0362	0.00898	0.0177	kg P-Eq
EQ. ionising radiation	1.80E-05	1.44E-05	5.20E-06	mol N-Eq
EQ. marine eutrophication	0.208	0.0183	0.0549	kg N-Eq
EQ. terrestrial eutrophication	1.61	0.196	0.706	mol N-Eq
HH. carcinogenic effects	5.16E-06	1.21E-06	2.52E-06	CTUh
HH. ionising radiation	4.74	3.08	1.25	kg U235-Eq
HH. non-carcinogenic effects	2.92E-05	5.77E-06	1.21E-05	CTUh
HH. ozone layer depletion	1.17E-05	4.75E-06	4.14E-06	kg CFC-11-Eq
HH. photochemical ozone creation	0.293	0.079	0.233	kg ethylene-Eq
HH. respiratory effects. inorganics	0.103	0.0175	0.0552	kg PM2.5-Eq
RS. land use	3.02E+04	77.4	78.6	kg Soil Organic Carbon
RS. mineral. fossils and renewables	0.0157	8.44E-04	0.00221	kg Sb-Eq

For the improved energy efficiency scenario the same energy usage as for MDF is assumed. This energy usage is 221 kWh electricity and 1116 MJ heat per 1m3 MDF (Werner, 2014). The amount of MDF in a 1m2 plate is 0.012m3 based on a density of 700kg/m3 (allesovermdf.nl, n.d.). The weight of a Re-plex plate is 9.6kg/m2. This results in the following energy usage per 100kg of Re-plex:

$$221\ kWh/m3\ MDF\ * \frac{\frac{0.012m3}{m2}MDF}{\frac{9.6kg}{m2}Re-plex} * 100kg = 27.625kWh/100kg\ Re-plex$$

$$\frac{1116MJ}{m3}MDF \quad * \frac{\frac{0.012m3}{m2}MDF}{\frac{9.6kg}{m2}Re-plex} * 100kg = 139.5MJ/100kg\ Re-plex$$

For the reduced Kaumera transport a transport distance of 108km from Zutphen to Amsterdam is assumed. The 32.13kg Kaumera that is added in dry form is assumed to be dried before transport. The Kaumera gel has a dry weight of 7%. This result in the following transport requirement per 100kg of Re-plex:

$$(20.08kg\ Kaumera\ gel/100kg\ Re-plex + 32.13\ kg\ Kaumera\ dry/100kg\ Re-plex) * 108km = 5.64ton * km$$

Single score indicator

In the Dutch building sector a standardised measure for the impact of building materials is the Mileu-Kosten Indicator (MKI). This is a single score indicator based on the chacterisation results from the CML impact assessment family. The MKI uses weighing factors to produce a single score in envrionmental costs (EC). The weighing factors from the Dutch National Environmental Database have been used (Stichting Nationale MilieuDatabase, 2020). The CML impact assessment family indicator results, and the single score result for the standard Re-plex model, the improved Re-plex production model and the FR-MDF production model can be found in table A10.

Table A10: The MKI single score weighing factors for the CML baseline impact assessment family (table A). The CML-2001 impact assessment family characterisation results (table B). The MKI single score result for FR-MDF, the standard Re-plex model, and the New Re-plex scenario (table C).

A:

Impact category	Environmental impact weighing factor	Unit
Acidification potential	4	€/kg SO2-eq
Climate change	0.05	€/kg CO2-eq
Eutrophication potential	9	€/kg PO4-eq
Freshwater aquatic ecotoxicity	0.03	€/kg 1,4-DCB-eq
Human toxicity	0.09	€/kg 1,4-DCB-eq
Marine aquatic ecotoxicity	0.0001	€/kg 1,4-DCB-eq
Photochemical oxidation	2	€/kg C2H4-eq
Stratospheric ozone depletion	30	€/kg CFK-11-eq
Terrestrial ecotoxicity	0.06	€/kg 1,4-DCB-eq
Abiotic depletion of minerals	0.16	€/kg Sb-eq
Abiotic depletion of fossil fuels	0.000077	€/MJ

B:

Impact category	1 year 1m2 FR-MDF use	1 year 1m2 Re-plex use	1 year 1m2 New scenario Re-plex use	Unit
Acidification potential	0.001852	0.003241	0.00121	kg SO2-Eq
Climate change	0.40105	0.69949	0.279	kg CO2-Eq
Eutrophication potential	0.000585	0.001348	0.000528	kg PO4-Eq
Freshwater aquatic ecotoxicity	0.13423	0.23676	0.109	kg 1,4-DCB-Eq
Human toxicity	0.29196	0.39814	0.213	kg 1,4-DCB-Eq
Marine aquatic ecotoxicity	393.24	777.49	345	kg 1,4-DCB-Eq
Photochemical oxidation	0.000158	0.000142	6.35E-05	kg ethylene-Eq
Stratospheric ozone depletion	4.00E-08	8.01E-08	4.79E-08	kg CFC-11-Eq
Terrestrial ecotoxicity	0.002509	0.005808	0.00435	kg 1,4-DCB-Eq
Abiotic depletion of minerals	3.25E-05	5.99E-05	2.76E-05	kg Sb-Eq
Abiotic depletion of fossil fuels	6.335	10.132	4.75	megajoule

C:

	1 year 1m2 FR-MDF use	1 year 1m2 Re-plex use	1 year 1m2 New scenario Re-plex use	Unit
MKI single score	0.103	0.182	0.0812	€/(m2*year)

Sensitivity analysis

Below the characterisation results for the sensitivity analysis are given. The characterisation results for the inventory analysis assumptions can be found in table A11. The characterisation results for the methodological assumptions can be found in table A12.

Table A11: ILCD impact family characterisation results sensitivity analysis for the new Re-plex scenario. The sensitivity to inventory assumptions is calculated. The scenarios that have been studied are; 35% Kaumera extraction compared to 23%; 20 years lifetime compared to 32 years; 20% extra, or 20% less energy use.

Impact category	1 year 1m2 New scenario Re-plex use	1 year of 1m2 FR-MDF use	New Re-plex with 35% Kaumera extraction	New Re-plex with 20 years lifetime	New Re-plex with +20% energy requirement	New Re-plex with -20% energy requirement	Unit
Climate change	0.279	0.401	0.272	0.446	0.289	0.268	kg CO2-Eq
EQ. acidification	0.00152	0.00241	0.00147	0.00242	0.00154	0.00149	mol H+-Eq
EQ. freshwater ecotoxicity	2.52	3.45	2.4	4.03	2.58	2.46	CTUh.m3.yr
EQ. freshwater eutrophication	0.00011	0.000116	0.000103	0.000176	0.000114	0.000106	kg P-Eq
EQ. ionising radiation	1.13E-07	1.07E-07	1.05E-07	1.80E-07	1.16E-07	1.10E-07	mol N-Eq
EQ. marine eutrophication	0.000408	0.000596	0.000401	0.000654	0.000413	0.000404	kg N-Eq
EQ. terrestrial eutrophication	0.00336	0.00645	0.00333	0.00538	0.00344	0.00328	mol N-Eq
HH. carcinogenic effects	1.58E-08	3.16E-08	1.50E-08	2.52E-08	1.62E-08	1.54E-08	CTUh
HH. ionising radiation	0.0327	0.0245	0.0296	0.0523	0.034	0.0314	kg U235-Eq
HH. non-carcinogenic effects	1.18E-07	1.46E-07	1.11E-07	1.88E-07	1.19E-07	1.16E-07	CTUh
HH. ozone layer depletion	4.79E-08	4.00E-08	4.09E-08	7.66E-08	4.85E-08	4.73E-08	kg CFC-11-Eq
HH. photochemical ozone creation	0.000811	0.00163	0.00079	0.0013	0.000822	0.0008	kg ethylene-Eq
HH. respiratory effects. inorganics	0.00018	0.000477	0.000178	0.000289	0.000182	0.000179	kg PM2.5-Eq
RS. land use	29.4	3.54	29.4	47	29.4	29.4	kg Soil Organic Carbon
RS. mineral. fossils and renewables	2.72E-05	1.53E-05	2.44E-05	4.35E-05	2.72E-05	2.71E-05	kg Sb-Eq

Table A12: ILCD impact family characterisation results sensitivity analysis for the new Re-plex scenario. The characterisation results for the ReCiPe impact family (A) and the characterisation results for the energy-based- and economic allocation methods (B).

A:

Impact category	1 year 1m2 Re-plex use	1 year 1m2 FR-MDF use	unit
Agricultural land occupation	7.91E-02	6.14E-01	m2a
Climate change	0.278	0.399	kg CO2-Eq
Fossil depletion	0.097	0.131	kg oil-Eq
Freshwater ecotoxicity	3.43E-04	6.76E-04	kg 1,4-DCB-Eq
Freshwater eutrophication	2.02E-05	2.27E-05	kg P-Eq
Human toxicity	0.0453	0.111	kg 1,4-DCB-Eq
Ionising radiation	0.0147	0.0138	kg U235-Eq
Marine ecotoxicity	4.59E-04	7.18E-04	kg 1,4-DCB-Eq
Marine eutrophication	0.000188	8.31E-05	kg N-Eq
Metal depletion	0.0164	0.0258	kg Fe-Eq
Natural land transformation	0.00128	0.0148	m2
Ozone depletion	4.79E-08	4.00E-08	kg CFC-11-Eq
Particulate matter formation	0.000537	0.000863	kg PM10-Eq
Photochemical oxidant formation	0.000828	0.0017	kg NMVOC
Terrestrial acidification	0.00116	0.00186	kg SO2-Eq
Terrestrial ecotoxicity	0.000445	6.47E-05	kg 1,4-DCB-Eq
Urban land occupation	0.00445	0.0103	m2a
Water depletion	0.00192	0.00128	m3

B:

Impact category	1 year 1m2 New scenario Re-plex use (energy based allocation)	1 year 1m2 New scenario Re-plex use (Economic allocation)	1 year of 1m2 FR-MDF use	Unit
Climate change	0.2779	0.276	0.34629	kg CO2-Eq
EQ. acidification	0.001444	0.00151	0.002265	mol H+-Eq
EQ. freshwater ecotoxicity	2.3571	2.52	2.5594	CTUh.m3.yr
EQ. freshwater eutrophication	0.000105	0.00011	0.000104	kg P-Eq
EQ. ionising radiation	1.09E-07	1.13E-07	1.03E-07	mol N-Eq
EQ. marine eutrophication	0.000397	0.000404	0.00043	kg N-Eq
EQ. terrestrial eutrophication	0.003233	0.00334	0.005967	mol N-Eq
HH. carcinogenic effects	1.49E-08	1.57E-08	2.57E-08	CTUh
HH. ionising radiation	0.031526	0.0327	0.02371	kg U235-Eq
HH. non-carcinogenic effects	1.12E-07	1.18E-07	1.28E-07	CTUh
HH. ozone layer depletion	4.84E-08	4.78E-08	3.72E-08	kg CFC-11-Eq
HH. photochemical ozone creation	0.000781	0.000807	0.001525	kg ethylene-Eq
HH. respiratory effects. inorganics	0.000168	0.00018	0.000462	kg PM2.5-Eq
RS. land use	29.31	29.4	3.5106	kg Soil Organic Carbon
RS. mineral. fossils and renewables	2.50E-05	2.71E-05	1.50E-05	kg Sb-Eq