Washing as a Service

Quantifying the Environmental Impact of a pay-per-use washing machine through Life Cycle Assessment

Master Thesis Industrial Ecology

K.J. Steunenberg

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Quantifying the Environmental Impact of a pay-per-use washing machine through Life Cycle Assessment

By

K.J. (Kirsten) Steunenberg

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Delft student number:	4755294
Leiden student number:	1494929

Graduation Committee:

First supervisor:	Prof. Dr. Ir. C.A. Bakker	Industrial Design – TU Delft
Second supervisor:	Dr. Ir. J.B. Guinée	CML – Leiden University
Assistant supervisor:	L.T. Amatuni MSc	CML – Leiden University

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Preface and acknowledgements

This thesis is the last requirement of the Industrial Ecology programme that I have been following for the past two and a half years. I have always very much enjoyed studying and during this Master I have learnt more than I could have ever imagined. The complexity of sustainability problems is almost impossible to grasp, but nonetheless I feel confident when talking about sustainability and I am ready and thrilled for the years ahead. To finish off my Master programme in the second wave of the Corona pandemic is of course not something that I would have imagined. I must admit that I genuinely missed the proximity of my fellow students and being at University. However, *"that is just the way it is"* and I can be even more proud to have finished this thesis the way I did. I would like to take the opportunity here to thank the people who have helped and supported me for the past five months.

Foremost, I would like to express my gratitude to my supervisors Conny Bakker and Jeroen Guinée. Thank you for your guidance and your time to read my work and provide me with feedback. You are both a huge inspiration in your research fields and to us, as students. I also want to thank Levon Amatuni, for your feedback and for being available for my LCA questions.

Further, I want to thank the people from Gorenje and ATAG who have spoken with me, Simon Kotnik, Jan van Os, Maurice van Kippersluis and Marijan Grešnovik, for your time and answers. A special thank you to Aleš Mihelič for your enthusiasm and interest in my thesis; it has motivated me enormously. I hope this research contributes to Gorenje's work in adopting more sustainable business models and reducing the environmental impact of household appliances.

Thank you to those in the ReCiPSS project, Sonja van Dam and Farazee Mohammad Abdullah Asif, for your time to talk.

And last but not least, I owe a massive thank you to the people close to me. To my parents and brothers; I am so grateful for our family. To Wiebe, for your love and your endless understanding. And to my friends – you know who you are – for your support and all the good times. I like to especially thank my friends in the Industrial Ecology programme here, without you the programme would have been half the fun.

Leiden, January 2020

Kirsten Steunenberg

Executive summary

In order to live more sustainably on this planet, the world's population needs to transform the current take-make dispose society towards a society with more maintainable consumption patterns and more sustainable business models. A way to achieve this, is a circular economy in which value is maintained within the product cycle, by sharing, repairing, reusing, refurbishing and recycling. Product-service systems, such as leasing, sharing and pay-per-use models, are presented as a way to contribute to the circular economy.

Product-service systems (PSS) could potentially reduce environmental impacts, however, PSS do not automatically lead to positive environmental impacts and not all PSS are by default environmentally benign. Therefore, several authors call for quantifications of PSS' environmental impacts, because the benefits of PSS remain inexplicit in literature and are mostly qualitatively described.

Life Cycle Assessment (LCA) is a common method to evaluate the environmental impacts over a product's lifecycle. LCAs compare the function that products or services fulfil over their entire life cycle and over various impact categories. As such, they provide an appropriate method to assess PSS' environmental impacts.

This research conducts an LCA on a PSS, having the pay-per-wash washing machine of Gorenje as case study. The LCA compares the pay-per-wash washing machine to a washing machine that is sold in a traditional way. The research question answered in this research is: *under which conditions can a pay-per-wash model reduce environmental impacts compared to a traditional sales model?* To answer this question, the research is divided in three phases.

The **first phase** consists out of two literature reviews. The first literature review shows that PSS have the potential to reduce environmental impacts, but that PSS should not be regarded as inherently sustainable. PSSs should be designed with the goal of reducing environmental impacts and circularity in mind. Only in this way PSS can be environmentally benign compared to their traditionally sold counterparts. The second literature review presents challenges that could arise when modelling PSS through LCA and guidelines that are followed up, based on Kjaer et al.

The **second phase** is a full, attributional LCA, comparing two alternatives that will be referred to as the **sales model** and the **PPW (pay-per-wash) model**. In the sales model, the washing machine is 'traditionally' bought and used by a household and reaches its end-of-life after 12 years on average. In the PPW model, Gorenje stays owner of the washing machine and the household enters into a contract with Gorenje. The household pays per wash and Gorenje installs, repair and refurbishes the washing machine. The coverage of processes is production, use and end-of-life for the sales model and production, use, repair, refurbishment and end-of-life for the PPW model. The selected impact categories are acidification, climate change, eutrophication, freshwater ecotoxicity, land use, photochemical oxidation, ozone layer depletion, resources: fossils and resources: minerals and metals and are all taken from the ILCD family. The functional unit is set at 1 year of washing a household's laundry.

The main assumptions of the LCA are listed below. The LCA with these characteristics will be referred to as the **baseline scenario**.

- The lifetime of the washing machine is 12 years in the sales model, compared to 24 years for the PPW model.
- The weight of the electronics component in the sales model is 0.9 kilograms, compared to 0.93 kilograms for the PPW model.
- A household runs 220 laundry cycles per year and, for the sake of simplicity, always chooses the 'standard cotton'-washing programme. This washing programme uses 1.3 kWh of electricity and 73 litres of water per laundry cycle.
- The household uses 0.08 kilograms of detergent per laundry cycle, the weight of the loading is 8 kilograms per laundry cycle. Over- and underloading are out of scope of this research, just as over- and underdosing detergent, auto-dosing detergent and the use of fabric enhancer.
- For the PPW model, the repair process consists of a service engineer driving 100 kilometres in a passenger car and replacing the pump motor. The refurbishment process consists of taking the washing machine in a small lorry to the service centre (11.4 tkm), cleaning the washing machine and replacing the heater, 0.5 bearings and 0.5 pulley.

Main results of the LCA are the following:

- The sales model has larger environmental impacts than the PPW model, for all impact categories. If ReCiPe impact categories are taken into account, the sales model has larger environmental impact for all impact categories, **except for** urban land occupation and terrestrial ecotoxicity.
- The **use phase** contributes most to the total environmental impact of both the sales and PPW model, followed by the repair process for the PPW model. The impact category resources: minerals and metals is for 88% (sales model) and 67% (PPW model) explained by the production process.
- The type of electronics in the washing machine and a country's electricity mix influence the outcomes notably.
- If the lifetime of the PPW model is not extended to more than 12 years, it will **most likely not reduce** environmental impacts compared to the sales model.

The **third** and **last phase** of this research consists of an analysis on different types of user behaviour and consequently, a way to optimise the PPW model.

Four user types are defined:

- User type A ('care-free YUP'): washing a low number of laundry cycles at 30-40°C;
- User type B ('eco conscious'): washing a low number of laundry cycles, mostly at 30°C or colder;
- User type C ('multitasking fam'): washing a high number of laundry cycles at various temperatures;
- User type D ('germophobe'): washing a high number of laundry cycles at 40 or 60°C.

The analysis shows that user type C has the largest environmental impact, closely followed by user type D. Furthermore, it demonstrates that the type of user (and its behaviour) is an important factor in determining the environmental impact of the sales and PPW model.

Afterwards, two effects are discussed: the rebound effect and the effect after introduction of a PPW model. The latter is referred to as the 'price incentive': consisting out of a minimum amount per wash and a proportionally higher amount for laundry cycles at warmer temperatures. Such a price incentive has proven to be able to reduce a household's average number of laundry cycles and the average washing temperature.

Incorporating the price incentive into the LCA model presents the following results:

- **Compared to the sales model**, the **PPW model with price incentive** can reduce environmental impacts:
  - with at least 25% and up to 40% for the baseline scenario;
  - with about 25% for user types A and B, ranging between 10% up to 40% reductions;
  - with about 25%-30% for user types C and D, ranging between 15% up to 40% reductions.
- **Compared to the PPW model without price incentive**, the **PPW model with price incentive** can reduce environmental impacts:
  - with at least 5% and up to 35% for the baseline scenario, with 20%-25% on average;
  - with about 5% to 10% for user types A and B;
  - with about 10% to 25% for user types C and D.

The last part of the third phase suggests a way to further optimise the PPW model. The **optimal PPW model** includes the following characteristics:

- The weight of the electronics component is utmost 0.9 kilograms;
- The consumer uses three washing programmes (standard cotton + Eco-button, easy care and hand wash). This reduces the average electricity consumption to 0.62 kWh per laundry cycle and the average water consumption to 56.5 litres per laundry cycle;
- The price incentive is adopted, consisting out of a minimum amount per wash and a proportionally higher amount for laundry cycles at warmer temperatures;
- 10% of the consumed electricity comes from PV panels;
- The service engineer drives 25 kilometres in a fuel efficient car;
- The contract duration per customer is extended to 5 years.

This optimal PPW model reduces the environmental impact **compared to the PPW model** in the **baseline scenario** for all impact categories with at least 26%. Reductions are largest for climate change with 47% and resources: fossils with 48%.

All things considered, this research concludes that a pay-per-wash model can reduce environmental impacts compared to a traditional sales model if the following conditions are met. Firstly, the lifetime of the PPW model needs to be extended by repair and refurbishment, 'designing-to-last' and extending the use phase of the washing machine by contract duration and serving multiple customers with one washing machine. This research presents that if this condition is not met, the reduced environmental impact of the PPW model is not a given. The added repair and refurbishment process should not diminish the positive environmental impact from the extended lifetime. Secondly, the PPW model can incentivise customers to wash less often and at lower temperatures. The payment structure and incentives in a PPW model make it easier to achieve environmentally sustainable laundry behaviour than in a sales model.

All in all, the physical difference between the sales model and the PPW model is not so considerable and it does not provide the condition to reduce environmental impacts. It is the lifetime extension of the washing machine – with the incentive for producers to design with circularity in mind and take responsibility for maintenance and repair – together with sustainable consumer behaviour, which can be more easily affected in a PPW model than in a sales model, that provide the conditions to reduce the environmental impact of a PPW washing machine.

Recommendations for Gorenje are:

- Incorporating a price incentive into the PPW model;
- Investigating the habits and wishes of customers and focusing on households with high numbers of laundry cycles and washing at higher temperatures, since that is where largest environmental reductions can be achieved. They can be reached by tailoring the marketing of the PPW model towards their habits and wishes;
- Further reducing the environmental impact of the PPW model is done by focusing on the production process and repair process.

Recommendations for future research are:

- Research into the behavioural variance of customers, customers' behaviour after introduction of a PPW model and rebound effects after introduction of the PPW model;
- Research into the Activity Browser's ability to handle circular economy products.

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Chapter 1: Introduction

1.1. Context and background information

The world's population has been strongly growing over the past decades and is anticipated to increase further from 7.7 billion persons today to 9.7 billion persons in 2050 (United Nations, 2019).

At the same time, human's consumption per capita is also on the rise. Worldwide raw material consumption increased by 60% since 1980 (OECD, 2015). Moreover, the global middle class is predicted to increase from 1.8 billion persons in 2009 to 4.9 billion persons in 2030 (Pezzini, 2012). This is mostly due to people in Asia coming out of poverty and increasing their consumption in, for example, refrigerators, cars, washing machines and televisions.

The increase of our world's population and human's consumption per capita taken together causes scarcity of earth's resources (IPCC, 2019). Furthermore, the environment is becoming more and more polluted with the sharp growth in greenhouse gas emissions – 70% between 1970 and 2004 – as one of the most urgent problems (IPCC, 2007). To solve these problems, we will need to live more sustainably on this planet. Sustainable development is famously phrased in the Brundtland report as: *"meeting the needs of current generations without compromising the ability of future generations to meet their needs"* (Brundtland et al., 1987, p. 16).

A solution to living more sustainably is a transformation of our current take-make-dispose society towards with a society with maintainable consumption patterns and more sustainable business models (Bocken et al., 2014, 2019; MacArthur, 2013). While sustainable consumption and sustainable business models have been addressed in various forms, names and concepts (like closed loop models, b-corporations, industrial symbiosis (Bocken et al., 2014)), two concepts require more introduction in this place: circular economy and product-service system.

The circular economy philosophy calls for action to maintain value within the product cycle: share, maintain/repair, reuse, refurbish and recycle (Ghisellini et al., 2016; MacArthur, 2013). MacArthur (2013, p. 7) defines the circular economy as *"an industrial system that is restorative or regenerative by intention and design"*. This definition is famously illustrated by the butterfly graph, in which the economy is divided in a technical and biological system. The technical system consists out of several loops, where the inner loops are preferred over the outer loops: maintenance is preferred over reuse, reuse over refurbishment and refurbishment over recycling (MacArthur, 2013). Product-service systems (hereafter: PSS), such as leasing, sharing and result-oriented systems, are presented in literature as a way to contribute to the circular economy (Bocken et al., 2017; Da Costa Fernandes et al., 2020; Tukker, 2004). The concept is defined as (Tukker & Tischner, 2006, p. 1552):

> "*A Product-Service System consists of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling specific needs of customers."*

PSS are classified in three main categories (Tukker, 2004):

- Product-oriented services: the business model is still focused on the sales of products, but additionally some services like maintenance are offered. Other examples within this category are a take-back agreement for when the product reaches its end of life or advice on most efficient use of the product.

- Use-oriented services: here, the producer remains owner of the product and the customer can use it, sometimes sharing it among a number of people. The business model is not focused on the sales of products, but on the customer using the product. Examples are leasing of household appliances and car sharing and pooling systems.
- Result-oriented services: the producer/provider and the customer agree on a result, without necessarily providing a product to the customer. An example of this is outsourcing, where a service like cleaning or party planning is outsourced to a third party and the provider and customer agree on the end result that needs to be realised. Another form of result-oriented service is 'pay-per-service unit', in which the customer pays for the output of the product, according to the amount that is used. The provider is responsible for supply, maintenance, repair and replacement.

Tukker (2004) expects that environmental benefits can be achieved in the 'pay-per-service unit' (hereafter: pay-per-use) because the provider is responsible for all life cycle costs, which gives a powerful incentive to design a product most efficiently over its entire life cycle. Also, customers could use the product more consciously, since they pay per use (leading to a less-use situation).

This thesis studies the environmental impact of a pay-per-use business model – in this case a washing machine. A comparative Life Cycle Assessment (introduced below) assesses the environmental impact of a pay-per-wash washing machine of the Gorenje company and compares this new business model to a washing machine that is sold in a traditional way. The next section presents the problem statement that underlies this research.

1.2. Problem statement and knowledge gap

As introduced above, PSS are often proposed as a way to contribute to a circular economy. PSS could potentially reduce environmental impacts (Bocken et al., 2017; Kjaer et al. 2016). However, PSS do not automatically lead to positive environmental impacts and not all PSS are by default environmentally benign (Catulli & Dodourova, 2013; Heiskanen & Jalas, 2003; Mont, 2004; Pigosso & McAloone, 2016; Tukker 2004; Tukker & Tischner, 2006). Therefore, several authors call for quantifications of PSS' environmental impacts (Beuren et al., 2013; Chen & Huang, 2019; Kjaer et al., 2018; Tukker, 2015).

Life Cycle Assessment (hereafter: LCA) is a common method to evaluate the environmental impacts over a product's lifecycle (Chen & Huang, 2019; Kjaer et al., 2016; Zhang et al., 2018). The concept and methodological steps are defined in ISO14040 standards (ISO, 2006). In these standards, a 'product' is defined as a good *or* service and as such, LCA would be suitable for assessing the environmental impact of product-service systems in the same way as it assesses the environmental impact of a sole good (Kjaer et al., 2016). Additionally, in comparative LCAs not the tangible products are compared, but the functions they fulfil (Guinée et al., 2002). This makes it possible to define a product-service systems' function and perform an LCA to assess its environmental impacts.

Hence, environmental impact assessments of several types of PSS are needed and the LCA method provides an appropriate way to do this. The laundry and washing machine market seems very suitable as PSS (Grazia Gnoni et al., 2017). The washing machine market is now very dependent on product lifetime and customers are mainly driven by the price of washing machines, where they often choose so-called 'entry-level' machines that are cheaper than high-end machines. However, in the long run, high-end machines are more energy efficient and 55% cheaper per washing cycle than entry-level machines (Grazia Gnoni et al., 2017). Traditional sales and business models nevertheless still push customers towards these seemingly cheaper entry-level machines. By switching to a pay-per-use model, the customer gets access to a high-end, energy efficient washing machine and can spread the involved costs over several months. Furthermore, the producer gains control and becomes closely involved in the maintenance and end-of-life phase, potentially extending the products lifetime and optimising its recycling (Grazia Gnoni et al., 2017).

Washing machines comprise the largest share of household appliances by mass. 22% of the total mass of all new household appliances bought in the EU annually comes from washing machines (Wasserbaur, 2020). Besides, the electricity used in washing makes up a substantial share of households' total energy consumption. Households are, with 29.7% of the total, the second most consuming sector of energy, only preceded by the industry sector (Pakula & Stamminger, 2010). Within households, 7.2% of electricity is used for washing and drying (compared to for example 19.1% for heating and 10% for lighting) (Bertoldi et al., 2012). Pakula and Stamminger (2010) estimated the energy consumption for laundry washing alone to be 24.2 TWh/year in Europe. Reducing the electricity consumption of doing the laundry by switching to a more energy efficient washing machine or a PSS could reduce environmental impact of doing the laundry.

For years, laundromats have already offered washing as a service in various forms; with potential positive environmental effects (Amasawa et al., 2018; Haapala et al. 2008; Heiskanen & Jalas, 2003; Hu, 2012; Moon et al., 2019). Today, pay-per-use models for washing machines are upcoming in the Netherlands and offered by for example Bundles and HOMIE. A study on the environmental impact of HOMIE has been done, with promising results. The pay-per-wash business model was effective at changing consumer behaviour and reduced the average washing temperature and average number of laundry cycles (Bocken et al., 2018). However, to the best of this author's knowledge, no LCAs on such designs for washing machines exist. Bocken et al. (2018, p. 500) even call for an environmental impact assessment of a pay-per-use model for washing machines, in their paragraph on 'future work':

> *"Few studies quantitatively assess the environmental impact of PPS and this is even more rare for pay-per-use business models as a specific type of PSS. […] We acknowledge that more research is needed to determine the overall environmental impact of a pay-per-use model for washing machines."*

This research performs an LCA on the pay-per-wash washing machine of Gorenje, compared to a Gorenje washing machine that is sold in a traditional way. As such, it contributes to filling the gap on quantifications of PSS and potentially reducing the environmental impact of doing the laundry, which makes up a substantial share in household electricity consumption.

1.3. Research question and sub questions

By performing an LCA, this thesis quantifies the environmental impact of a pay-per-wash model of a Gorenje washing machine. This thesis answers the following research question:

"Under which conditions can a pay-per-wash model reduce environmental impacts compared to a traditional sales model?"

To answer this research question, the following sub questions are answered:

1. What is the environmental potential of product-service systems and what environmental potential can be expected for the pay-per-wash washing machine?
2. Which challenges and problems could arise when modelling product-service systems through LCA and what ways are suggested to overcome these challenges?
3. What are the environmental impacts per impact category of the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?
4. How do several user scenarios change the outcome in environmental impacts related to the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?
5. What kind of user behaviour can be expected after the introduction of the pay-per-wash model and how would this behaviour change the outcome of the LCA?
6. How can the Gorenje pay-per-wash model be further optimised and which (behavioural) changes are needed to achieve this?

1.4. Report structure

The overall research approach of this thesis is described in chapter 2 below. Afterwards, this report is structured as follows, where each subsequent chapter deals with one sub question. Chapter 3 discusses the environmental potential of product-service systems in general and based on that, the environmental potential of the pay-per-wash washing machine. Chapter 4 explores which challenges and problems could arise when modelling PSS through LCA. Chapter 3 and chapter 4 are both based on literature reviews. Chapter 5 then performs a full LCA, following the methodological steps as defined in the ISO14040 standards. Afterwards, the LCA model and results of the LCA are used to deepen the knowledge on this case to be able to answer the conditional nature of the research question. Chapter 6 defines four user types to discover how these user types change the outcomes of the LCA. Next, chapter 7 discusses rebound effects and other user behaviour that could arise after introduction of the pay-per-wash model. Chapter 8 deals with the last sub question and proposes a way to further optimise the pay-per-wash model. All this is put together in chapter 9 and 10; chapter 9 places the results in a wider context in the discussion and chapter 10 concludes this research by answering the research question.

Chapter 2: Research approach

This research follows the LCA approach. The LCA approach prescribes four phases that are needed to conduct an LCA: goal and scope definition, life cycle inventory analysis, impact assessment and interpretation. This research is however more encompassing than just the sole performance of an LCA. The LCA is preceded by two literature reviews, focused on the environmental potential of product-service systems and the challenges that could occur while modelling a PSS through LCA. The literature reviews are followed up by the LCA, in which the four phases as mentioned above are followed. The results of the LCA are used for further analysis considering several types of user behaviour and behavioural effects that could occur after introduction of the pay-per-wash model. The approach and steps taken in this research are visually represented in figure 1 below. The methods for each chapter are elaborately discussed in the introduction of each chapter.

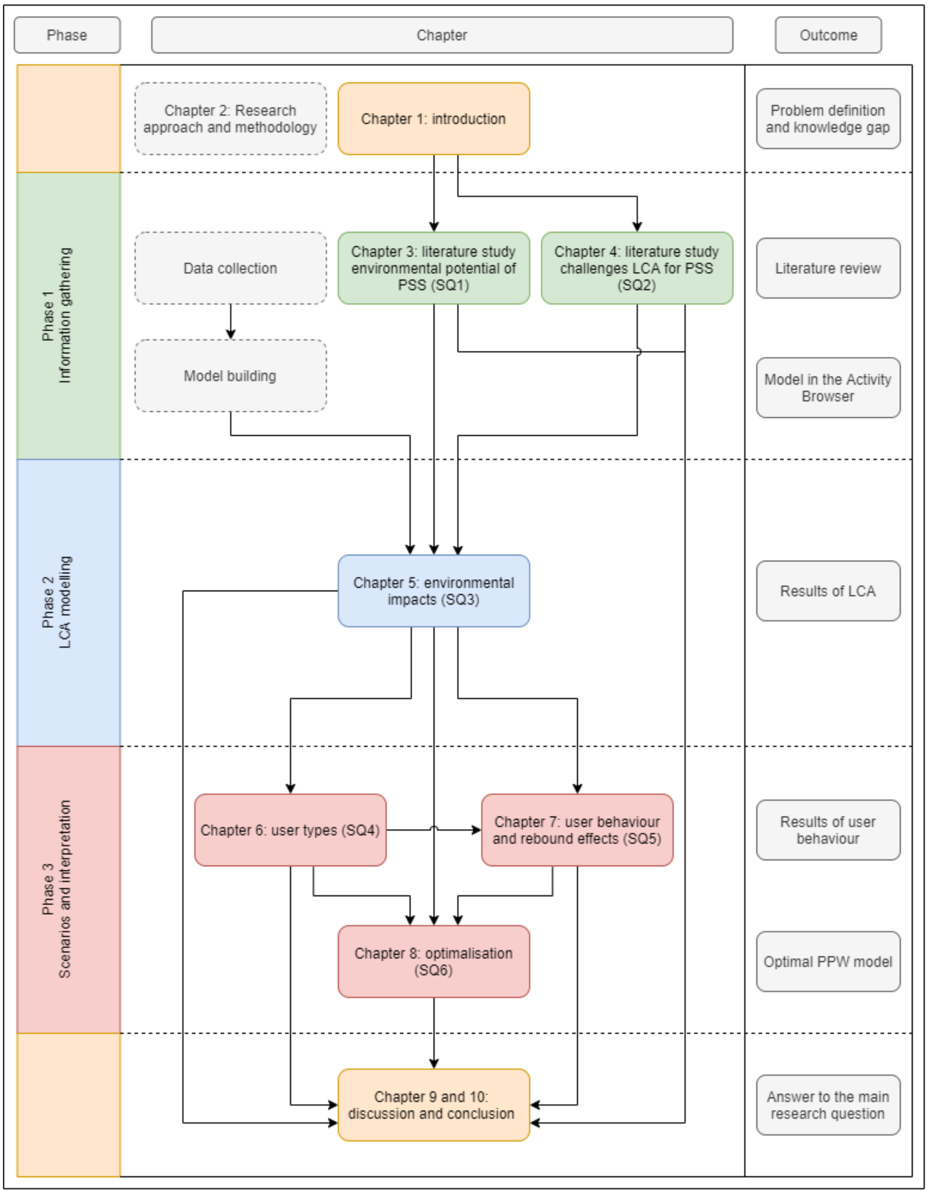

Figure 1: Research flow diagram including the components and interlinkages of this thesis

Chapter 3: The environmental potential of Product-Service Systems

What is the environmental potential of product-service systems and what environmental potential can be expected for the pay-per-wash washing machine?

This chapter first discusses the methodology in section 3.1 and afterwards discusses the environmental potential of product-service systems as discussed in literature in section 3.2. Section 3.3 discusses other LCAs on washing machines and laundry services, to assess the environmental potential of the pay-per-wash washing machine of Gorenje. Section 3.4 summarises the results and answers this chapter's sub question.

3.1. Methodology

Chapters 3 and 4 are the result of two separate systematic literature reviews, in which structured literature searches lead to two lists of key papers that were thoroughly read, structured, summarised and discussed. The research questions of the respective chapters were turned into search terms. To maximise output and to minimise the chances of missing out on relevant literature, synonyms and related concepts were replaced in the search term. Abstract database Scopus was used to search for papers. The search terms for chapter 3 were as follows:

Table 1: Search terms and corresponding amount of hits for chapter 3

Concept 1		Concept 2		Concept 3	Number of hits
"Sustainab*"	AND	"Product-service system"			682
"Environmental impact*"	AND	"Product-service system"			138
"Environmental benefit*"	AND	"Product-service system"			29
"Environmental benefit*"	AND	"Sharing economy'[1]			22
"Environmental benefit*"	AND	"Lease"			20
"Drawback*"	AND	"Product-service system"			10
"Drawback*"	AND	"Product-service system"			5
"Environmental potential"	AND	"Product-service system"			5
"Positive result*"	AND	"Product-service system"			3
"Environmental advantage*"	AND	"Product-service system"			3
"Sustainab*"	AND	"Product as a service"			3
"Sustainab*"	AND	"Washing as a service"			2
"Environmental benefit*"	AND	"Sharing"	AND	"Washing machine"	2
"Environmental benefit*"	AND	"Sharing"	AND	"Laundry"	2
"Environmental saving*"	AND	"Product-service system"			1

[1] The sharing economy is out of scope of this research, since the sharing economy is usually referred to when speaking about, for example, sharing platforms and sharing cars or tools between neighbours. The search term was thus added to widen the scope to see what kind of results would come up.

“Environmental benefit*”	AND	“Pay-per-use”			1
		“Product service economy”			1
“Environmental advantage*”	AND	“Pay-per-use”			0
“Environmental saving*”	AND	“Pay-per-use”			0
“Environmental saving*”	AND	“Lease”			0
“Environmental benefit*”	AND	“Product-service system”	AND	“Washing machine”	0
“Environmental benefit*”	AND	“Product-service system”	AND	“Laundry”	0
“Environmental benefit*”	AND	“Use-based business model”			0
“Environmental benefit*”	AND	“Product as a service”			0
“Environmental benefit*”	AND	“Washing as a service”			0
“Environmental benefit*”	AND	“Product service economy”			0
“Environmental benefit*”	AND	“Product as a service”			0
“Environmental potential”	AND	“Product as a service”			0
“Environmental potential”	AND	“Product service economy”			0
“Sustainab*”	AND	“Product service economy”			0

The abstracts, titles and keywords of papers were read and judged on its suitability. The first selection criterium was if papers discussed the environmental potential, benefits or drawbacks of PSS. If this was not clear from the abstract, papers were selected if they had a circular economy focus, if they were a literature review or if they discussed laundry, washing machine or household appliances specifically. Papers were not selected if they were published before the year 2000, because that is roughly when the term product-service system was introduced (see section 3.2 below). The selected papers were saved and read in detail; this resulted in a list of key papers. Some of the key papers referenced to other useful literature, which were then also included in the literature review (backward snowballing).

After the first version of chapter 3 was made up, it had to be revised, laying some additional focus on more recent and broader literature in the product-service system research field. The search term for that search, performed in December 2020 was:

Table 2: Search terms and corresponding amount of hits for revising chapter 3

Concept 1		Concept 2	Number of hits
“PSS”	AND	“environment*”	2319
“Product-service system”	AND	“environment*”	666
“PSS”	AND	“literature review”	231
“Product-service system”	AND	“literature review”	201
“Product-service system”	AND	“circular economy”	148
“PSS”	AND	“circular economy”	88

Papers from that search were selected by the following criteria:

- Published in 2018, 2019 or 2020, or;
- Focus on sustainable design, or;
- Not dealing with IT product-service systems, or;
- Focus on circular economy or environmental sustainability, or;
- Being a literature review on product-service system literature

The list of key papers that were first selected, the list of papers found through snowballing and the list of selected papers from the latter search are included in Appendix A. Logically, duplicates were ignored.

3.2. Environmental potential of product-service systems

The concept of PSS has been around since the last decades of the 20th century and the actual term product-service system was first used by Goedkoop et al. in 1999 (Da Costa Fernandes et al., 2020). Authors such as Stahel (in 1982) and Schmidt-Bleek (in 1993) were among the first to find the potential benefits of PSS concerning sustainability and resource-efficiency (Tukker, 2015). In 1994, Stahel introduced the concept of sharing economy (Lindahl et al., 2014). In his research on the sharing economy, Stahel brought up the notion that the customer value of a product lies in using a product; not in owning a product (Stahel, 1994). This notion still underlies the concept of PSS today.

While older papers (e.g. Roy, 2000) have only addressed the benefits of PSS and presented it as a solely sustainable solution, more recent literature usually discusses the benefits and drawbacks. The main claim here is that PSS are not *inherently* more sustainable than providing the sole product (Chen et al., 2019; Kjaer et al., 2019; Tukker, 2004; Tukker & Tischner, 2006). Providing a ‘dirty’ product within a PSS, will not suddenly make the product less dirty. As Scheepens et al. (2016, p. 259) put it:

> *“When leasing is applied to increase market share of a ‘dirty’ product, it is damaging our environment, however, when leasing is applied to increase market share of a ‘clean’ product, it is beneficial.”*

Nevertheless, in theory, PSS have the potential to improve environmental sustainability for several reasons; these are discussed below.

Firstly, offering a product in a PPS can lead to dematerialisation, which means that less (or no) materials are used to deliver the same level of functionality to the user (Bech et al., 2019; Beuren et al., 2013). Additionally, when a consumer does not own the product but only uses its function, they become ‘dematerialised’ from that product. (Chen et al., 2019; Scheepens et al., 2016). Absence of ownership is only applicable to use- and result-oriented PSS and therefore these have a higher environmental potential (Chen et al., 2019).

Secondly, offering a product as PSS can extend the lifetime of the product (Bech et al., 2019; Tukker, 2004). Either by improving the product efficiency during the use phase – for example through advice on efficient product use - (Bech et al., 2019), or by prolonging the use life by maintenance and prevention of failing (Khan et al., 2018), products can be used for a longer period of time. Furthermore, products are nowadays sometimes landfilled before their physical or economical end-of-life, due to quickly changing technologies, shifting consumer preferences and strong market competition (Khan et al., 2018). These waste streams harm the environment. By extending the lifetime of a product, the flow of materials through the economy is slowed down and the impact on the environment is reduced (Khan et al., 2018).

Thirdly, PSS can optimise the end-of-life phase of a product (Copani & Behnam, 2018; Kühl et al., 2018; Pialot et al., 2017). Products offered in a PSS can be taken back more easily, remanufactured or recycled for its parts after use. When the provider remains owner of the product, the end-of-life product still has value for the provider (Pialot et al., 2017). This can lead to optimised remanufacturing or recycling practices, whereas otherwise the product would have been more effortlessly discarded.

Lastly, PSS can incentivise producers towards environmental sustainability (Kühl et al., 2018). For example, if producers earn more money by minimising natural resource use than by selling as much as possible, producers are incentivised to innovate in ways that benefit the environment (Plepys et al., 2015). Also, if producers remain owners of the products, they are incentivised to minimise the costs per service unit and thus to optimise their material use (Kühl et al., 2018).

Although PSS thus have the potential to enhance environmental sustainability, several authors stress the importance of the design phase of a PSS. For a PSS to be sustainable and to guarantee resource efficiency, they should be purposely designed with this goal in mind (Baldassare et al., 2020, Bertoni, 2019; Beuren et al., 2013; Pigosso & McAloone, 2015; Vezzoli et al., 2015). The environmental impact of the newly designed PSS is determined during the early stages of the design process and so, designers need to be aware of these environmental impacts to design inherently sustainable PSSs (Neramballi et al., 2020). Da Costa Fernandes et al. (2020) state that also the value proposition of a PSS business model should be designed with circularity in mind. The environmental potential of a PSS is determined in the design phase, where *"the value proposition design should follow life-cycle thinking approach, i.e. the activities performed in the middle-of-life and end-of-life must be considered since the beginning-of-life"* (Da Costa Fernandes et al., 2020, p. 11).

All in all, product-service systems have the potential to reduce environmental impacts, – by dematerialisation, extending the product's life time, optimising its end-of-life and incentivising producers towards environmental sustainability – but PSSs need to be deliberately designed to achieve environmental benefits. Moreover, this potential is mostly described qualitatively and remains somewhat inexplicit in literature, as also acknowledged by Blomsma et al. (2018). The literature is also more focussed on positive environmental effects of PSS than on negative environmental effects. Blüher et al. (2020) conduct a systematic literature review on effects of PSS and find that positive environmental impacts of PSS are disproportionally often described, potentially indicating a publication bias (which they cannot prove statistically). This reflects the general positive connotation that PSS might have in literature (Blüher et al., 2020).

Researchers thus agree that PSS have the potential to reach environmental benefits; but environmental benefits do not necessarily occur in a PSS. Its design is crucial and the environmental impact depends per case. Several authors have summarised this by the phrase: 'PSS are not the sustainability panacea' (Catulli & Dodourova, 2013; Heiskanen & Jalas, 2003; Mont, 2004; Tukker, 2015).

3.3. Washing machine and laundry case studies and their environmental potential

Now knowing that product-service systems have in theory the potential to reduce environmental impact, the question raises how this potential works out for the case of washing machines or PSSs in the form of laundry/laundromat services. This section discusses other LCAs that are done in the field, to be able to hypothesise what potential the pay-per-wash model of Gorenje could have in reducing environmental impacts.

Ardente and Mathieux (2014) focus in their study on the trade-off between extending a washing machine's lifetime and the improved energy-efficiency of the newest washing machines. They cite a study which found that 90% of the environmental impacts of washing machines occur in the use phase, which would advocate for energy use efficiency instead of extending the lifetime. However, other authors state that improvements in the use phase do not compensate for environmental impacts in the production phase. Ardente and Mathieux (2014) perform an LCA with "Global Warming Potential (GWP), Terrestrial Ecotoxicity and Abiotic Depletion Potential (ADP)" as impact categories (*correction by author: climate change and abiotic depletion (AD) are impact categories, not GWP and ADP).* From that LCA it is found that extending the lifetime of the washing machine can lead to some environmental benefits, even if that prevents the replacement of these machines by more energy-efficient ones. However, the benefits are variable and depend on the impact category, the duration of the lifetime extension and the energy-efficiency of the replaced product. Benefits are mostly observed for AD.

Boldoczki et al. (2019) perform an LCA on the end-of-life phase of (among others) washing machines. Their study finds that reuse of washing machines is not always preferable over recycling. This builds on the same issue as discussed in Ardente and Mathieux (2014), since washing machines become more energy-efficient over time and therefore old ones should be replaced. Boldoczki et al. (2019) find that this is true for washing machines rated at energy label A or worse. They also note that user behaviour may impact the environmental impact of the use phase and that a country's electricity mix strongly effects the impact of electricity use.

Yamaguchi et al. (2011) focus on washing and drying, comparing heatpump washer-dryers to conventional washer-dryers. The heatpump washer-dryer reduced CO_2-eq. emissions with 30% compared to conventional washer-dryers, but it consumes more detergent.

Schmitz and Stamminger (2014) analyse the user behaviour of European citizens for washing and drying, based on an online questionnaire (note: without the use of LCA; the Netherlands as a country is not included). Their literature review shows that the consumer's behaviour is more influential in the environmental impact of the machine than the energy-efficiency of the machine. Some of the results are the following. An average European household consumes on average 396 kWh/year, from which only 30% can be dedicated to the washing itself (the other 70% is mostly drying). 3.8 washing cycles are on average done per week per household. Washes are most frequently done at 40°C. 'Mixed cotton' and 'cotton' are the most frequently used programmes.

Bracquené et al. (2020) develop a "Product Circularity Indicator (PCI)" which aims to measure the circularity of the flows within the system. They test the PCI by performing an LCA on a washing machine. The functional unit is "one WM for clothes washing, with a lifetime expectancy of 2500 wash cycles". In the sensitivity analysis of the LCA, they also take a PSS strategy into account, where the producer remains owner of the washing machine and the washing machine is refurbished every 6 years. The LCA results show that the use phase has the highest environmental impact and that printed wiring boards have a significant contribution to the total environmental impact. Also, *"the LCA results confirm the envisioned PSS strategy will both increase the circularity and reduce the environmental burden of the product system if the WM can indeed be successfully refurbished every 6 year and the majority of the components can be reused 3 times"* (Bracquené et al., 2020, p. 10).

Laurenti et al. (2014) perform a literature review on LCAs concerning washing machines to discover what functional units, life cycle stages and system boundaries are commonly used. They state that although most LCAs neglect behavioural effects, the product system should represent a combination of both physical and behavioural structures.

Hu (2012) compares the emissions in CO_2 eq. from 'traditional' washing machines with self-service laundries (which he groups under PSS) in an LCA. Two scenarios are investigated: the lifetime of 7 years, based on the traditional washing machine, and the lifetime of 21 years, based on a laundromat. Both scenarios show more favourable results for the self-service laundries, with 64,310 kg CO_2 eq. for scenario 1 and 160,532 kg CO_2 eq. for scenario 2 (compared to 155,276 kg CO_2 eq. and 465,830 kg CO_2 eq. respectively for the traditional washing machine).

Shahmohammadi et al. (2018) state that consumer behaviour can heavily influence the environmental impact of washing, but since the range of different consumer behaviours is often neglected in LCAs, they call for including the variability of consumer behaviour. They show how the inclusion of consumer behaviour data into LCA, results in the presentation of variability in greenhouse gas emissions for doing the laundry. From their analysis, influencing factors for the total greenhouse gas emissions were found to be a country's electricity mix and consumer behaviour. The average greenhouse gas emissions per laundry cycle, based on an analysis in 23 European countries in 2014, were found to be 500 grams CO_2 eq. The variability was a factor 6.5 between different countries and a factor 3.5 to 5.0 within the same country.

3.4. Chapter summary and conclusion

This chapter reviewed literature on the environmental potential of PSS and environmental impacts of washing machines, aiming to answer the following sub question: *what is the environmental potential of product-service systems and what environmental potential can be expected for the pay-per-wash washing machine?*

The potential of PSS to reduce environmental impacts is existent, but PSS should not be regarded as inherently sustainable. The benefits of PSS are mostly described qualitative and remain inexplicit in literature. Furthermore, authors stress that the design phase for PSS is important, to design with the goal of reducing environmental impacts and circularity in mind and that only in this way PSS can be environmentally benign compared to their traditionally sold counterparts.

All the above is also applicable to the potential of a pay-per-use washing machine to reduce environmental impacts. Additionally, previous case studies and LCAs have shown that extending the lifetime of the washing machine can lead to some environmental benefits. The studies found also that the use phase is largely contributing to the total environmental impact and that consumer behaviour influences the results. This means that if a PSS can achieve to reduce impacts there, it has the potential to reduce environmental impacts. Other authors who performed LCAs on some sort of washing machine PSS (Bracquené et al., 2020; Hu, 2012) found promising results for such PSS offerings, compared to 'traditional' washing machines.

Chapter 4: Modelling Product-Service Systems through Life Cycle Assessment

Which challenges and problems could arise when modelling product-service systems through LCA and what ways are suggested to overcome these challenges?

The separate scientific research fields of the PSS and LCA concepts have a relatively long history. However, the combination of the concepts is still emerging in scientific literature. Kjaer et al. (2016) found that only 11 articles were published between 2000 and 2015 on evaluating a PSS case study through LCA. Since 2014, integrated literature on PSS and LCA has been increasing and started to rapidly grow in 2016 and 2017 (Chen & Huang, 2019).

The methodology of this chapter is presented in section 4.1. The literature on challenges and problems that could arise when modelling PSS through LCA is then discussed in section 4.2. Afterwards, some proposed guidelines are discussed that could overcome the challenges in section 4.3. Section 4.4 summarises the results and answers this chapter's sub question.

4.1. Methodology

Chapter 4 followed the same methodology as described above for chapter 3. The search terms were:

Table 3: Search terms and corresponding amount of hits for chapter 4

Concept 1		Concept 2		Concept 3	Number of hits
		"Product-service system"	AND	"Life cycle assessment"	65
		"Laundry"	AND	"Life cycle assessment"	38
		"Washing machine"	AND	"Life cycle assessment"	36
"Challenge*"	AND	"Product-service system"	AND	"Life cycle assessment"	16
"Challenge*"	AND	"Product-service system"	AND	"Life cycle analysis"	8
"Challenge*"	AND	"Washing machine"	AND	"Life cycle assessment"	6
"Challenge*"	AND	"Product-service system"	AND	"Functional unit"	5
"Challenge*"	AND	"Product-service system"	AND	"Quantific*"	5
"Problem*"	AND	"Product-service system"	AND	"Life cycle assessment"	3
"Challenge*"	AND	"Laundry"	AND	"Life cycle assessment"	3
"Challenge*"	AND	"Product-service system"	AND	"Impact assessment"	3
"Challenge*"	AND	"Product-service system"	AND	"Reference system"	2
"Washing machine"	AND	"Product-service system"	AND	"Life cycle assessment"	1
"Barrier"	AND	"Product-service system"	AND	"Life cycle assessment"	1
"Problem*"	AND	"Product-service system"	AND	"Impact assessment"	1
"Obstacle"	AND	"Product-service system"	AND	"Life cycle assessment"	1
"Challenge*"	AND	"Product-service system"	AND	"Carbon impact"	0
"Problem*"	AND	"Product-service system"	AND	"Functional unit"	0
"Problem*"	AND	"Product-service system"	AND	"Reference system"	0
"Challenge*"	AND	"Laundry service"	AND	"Life cycle assessment"	0

Here, also the abstracts, titles and keywords of papers were read and judged on its suitability. Papers were selected if they evaluated or discussed a product-service system through the LCA method or if they discussed the LCA methodology focusing on services. For both chapters, the papers from the list were summarised and important, remarkable or contradicting issues were noted down. The chapters were set up from these notes. The list of key papers that were selected after the search for chapter 4 are included in Appendix A, supplemented by the list with papers from backward snowballing.

4.2. Challenges and problems

Doualle et al. (2015) argue that the classic LCA methods might not be appropriate for PSS, with as main challenge the definition of the functional unit. Whereas in classic LCAs the functional unit describes the functionality of a single product, the functional unit in PSS' LCAs needs to describe the functionality of a system of both products and services. In reality, however, the difference between an LCA on a PSS and non-PPS might not be as large as Doualle et al. (2015) suggest. LCAs on a single product ('non-PSS') still need to capture the functionality of the full product system, including both the product and the function (i.e. service) that it fulfils.

Kjaer et al. (2016) study which characteristics of PSS challenge their modelling in LCA and consequently formulate three main challenges. These challenges are defining the reference system, defining the functional unit and setting the system boundaries. First, it can be hard to determine the reference system to compare the PSS to, because LCAs on PSS are usually performed ex-ante (before implementation) and as a result, there is no data on how the market has changed after introduction of the PSS. This enhances the uncertainty of choosing the right reference system to compare the PSS to, since changes in the market could occur in the future. Furthermore, the chosen reference system determines the capability to include rebound effects in the LCA. Rebound effects could have been the result of behavioural changes after introduction of the PSS. A second challenge is the definition of the functional unit: neither too broad, nor too narrow; which is a challenge for all LCAs. However, Kjaer et al. (2016) emphasize that the functional unit in LCAs on PSS should be broad enough to capture changes in user behaviour as a result of PSS implementation. Changing user behaviour could appear over time and a too narrow functional unit would not be able to include the changed behaviour. Third, there exists a challenge in determining the system boundary. Which processes are included and excluded and how do you make sure that no severely contributing processes are excluded? Although this can be challenging in all LCAs, service providers do not create a lot of their impacts themselves at the site of activity, since impacts are usually created higher up in the supply chain, where the related products are manufactured (Kjaer et al., 2016).

A year after Kjaer et al.'s work, Dal Lago et al. (2017) complemented to that study, by formulating six challenges when modelling PSS through LCA and providing a first set of guidelines that was called for in Kjaer et al. (2016). Dal Lago et al. (2017) first discussed six challenges: scope, functional unit, system boundaries, service-related inventory, PSS reference system and end condition. Many of these challenges are not only specific challenges for modelling PSS in LCA, but LCA or modelling challenges in general. The uncertainty around rebound effects or the ex-ante nature of these LCAs could however further complicate the process. Dal Lago et al. (2017) argue that this is the main challenge concerning the scope: rebound effects in the PSS make it hard to compare it to a traditionally sold product. In addition, they warn for formulating the functional unit too narrowly, since it might not take into account all the sub-functions that a PSS could fulfil. They give the example of an LCA on transportation modes. Since a functional unit like ‘a passenger km in a car or a train’ would neglect behavioural changes, they formulate the functional unit as *“the actual transport behaviour of a person before and after joining the car sharing system, during a month”* (Dal Lago et al., 2017, p. 75). Furthermore, it is challenging to set up the inventory of materials, components and software that are behind a PSS, since indirect effects and rebound effects caused by the introduction of the PSS are hard to grasp. Lastly, Dal Lago et al. (2017) argue that the reference system of the PSS is usually the traditionally sold model added by pieces of software. Consequently, the PSS does not always have less impacts than the traditionally sold model, because the added pieces of software increase the raw material depletion category. This is however not really a challenge for modelling PSS in LCA and thus does not need to be further discussed in this place.

Sousa-Zomer and Miguel (2018) agree with a few of the challenges mentioned above, stating that the functional unit should include both products and services and account for all functions that are brought by the system.

Glatt et al. (2019) add some new challenges to the existing literature. Firstly, PSS have a bigger network of actors, stakeholders and partners which results in more complexity concerning the scope and system boundaries of the LCA. Secondly, PSS have longer and more complex life cycles (as also discussed in chapter 3) due to extended use phases, maintenance and reusing/recycling parts and products. Lastly, Glatt et al. (2019) state that core LCA literature does not perform many LCAs on PSS or discusses them conceptually, therefore further complicating the practical applicability.

Muñoz Lopez et al. (2020) discuss three challenges that are already previously mentioned: PSS having multiple life cycles, being a combination of both products and services and having unclear system boundaries.

Recently, Amasawa et al. (2020) called for a new approach in studying PSS through LCA. Since most studies compare the traditional sales model with one or two PSSs, separate studies on the same topic become really hard to compare. As a result, benchmarking PSSs on their environmental performance is difficult and it is even harder to determine which conditional factors determine the impacts in an LCA. Amasawa et al. (2020) therefore propose ‘one-to-many studies’, in which a traditional sales model is always compared to several distinguished forms of PSS. As such, it can be observed which factors influence the environmental performance. Although this is not a methodological challenge in combining PSS and LCA, it is nonetheless good to realise that just comparing two alternatives might not tell the whole story.

To conclude, these challenges can be framed two ways around. Some authors say: “the nature of LCA (being focused on tangible products and scope) challenges its applicability to PSS” (Bech et al., 2019), while other authors say: “the complex structure of PSS challenges its quantification in LCA” (Chen and Huang, 2019). Either way around, all authors argue for some evident challenges when modelling PSS through LCA. It is questionable whether these challenges really only apply to PSS, or that most of these challenges are LCA or modelling challenges in general. Also, despite these challenges, various scientists call for the evaluation of PSSs through LCA (Gnoni et al., 2017; Kjaer et al., 2018), since quantifications of PSS are lacking (Chen & Huang, 2019; Tukker, 2015). All this raises the question what ways can be used to overcome the abovementioned challenges.

4.3. Suggested ways to overcome the challenges

Dal Lago et al. (2017) develop guidelines to evaluate PSS by LCA, after Kjaer et al. (2016) had called for such guidelines. The guidelines are based on the ISO14040 framework and clustered around those stages: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. A year later, Kjaer et al. (2018) follow up on the identified challenges in Kjaer et al. (2016) and present guidelines in order to support those carrying out an LCA on a PSS. Their guidelines consist out of six steps, each step having two, three or four sub steps.

When comparing the guidelines (as done below) from Dal Lago et al. (2017) and Kjaer et al. (2018), it can be noticed that Kjaer et al.'s guidelines are more applicable and easier to use. Dal Lago et al. do not prescribe what a researcher should do, follow or take into account. An example of this is step 5:

> *"The equipment. The infrastructure is seen as the total amount of equipment used for running the PSS (e.g. 100 sensors, 40 gateways, 10 repeaters, few PCs, etc.). As presented in [4] the lifetime of the individual pieces of equipment used in a service infrastructure and the service infrastructure may differ. For example, defective equipment might be replaced or maintained"* (Dal Lago et al., 2017, p. 77).

In guidelines, one would expect some form of prescribing, advising or *guiding*, but that is frequently lacking in Dal Lago et al.'s guidelines. How different is this for Kjaer et al.'s guidelines. Every step is divided in sub-steps, making the tasks as small as possible. Furthermore, their guidelines are supplemented by three case studies that show how to use the guidelines in practice. Lastly, a detailed User Guide is developed (Kjaer et al., 2017), aimed at further assisting LCA practitioners.

Section 4.3.1 presents a short summary of the (vague) proposed guidelines by Dal Lago et al. (2017) and section 4.3.2 is a brief discussion of Kjaer et al.'s guidelines. Since the *guiding* is missing in Dal Lago et al. (2017), it was decided to follow Kjaer et al.'s guidelines in this thesis. Performing an LCA on a PSS requires a few additional think steps, especially in the goal and scope phase. Reflections, trade-offs and assumptions are discussed in Appendix B. Appendix B follows the sub-steps as described by Kjaer et al. (2018).

4.3.1. Guidelines Dal Lago et al. (2017)

Goal and scope

1. PSS description. It should be very clear what the PSS is and it is advised to follow Tukker's (2004) classification for this. Evaluating product-oriented services requires other points of attention than evaluating use-oriented services. It should also be clear what the sub-functions are that the PSS fulfils, because sub-functions need to be handled in the exact same way for different alternatives.
2. Functional unit. The functional unit should be broad enough to capture changes in user behaviour.
3. System boundaries. The goal and scope should clearly state the system boundaries, in line with the aim of the research.

Life Cycle Inventory

4. Data requirements. Because PSS are complex systems, consisting of multiple life cycles, multiple components, tangible products and intangible services, data can easily be neglected

or used in the wrong way. Therefore it is important to monitor the data quality, for example by a pedigree matrix.

5. The equipment. The equipment is the infrastructure around the PSS and the lifetime of the equipment might differ per alternative. The repairs and replacement of the equipment need to be taken into account.
6. The role of exchanged information. If the PSS requires different or more data exchanges than the reference system, this can lead to higher energy consumption which influences the use phase.

Life Cycle Impact Assessment

7. Impact categories and impact transfer. Here it is important that the results are not only compared by histograms showing the impact categories results, but also across the different life cycle stages and components.
8. Comparison of design alternatives. If sensitivity analyses are done to improve the design, these also need to be showed.

4.3.2. Guidelines Kjaer et al. (2018)

1. Goal definition. In this step, the study purpose, complexity and time and resources are established.
2. PSS and reference system exploration. Among others, this step defines the scope of the study: PSS consequences, PSS comparison or PSS optimisation. Furthermore, the reference system is explored and there is decided on what the PSS substitutes. Kjaer et al. (2018) distinguish between three types of PSS support: activity support, product support, platform support. Knowing the type of support, it becomes easier to determine the reference system.
3. Comparability assessment. In this step, the functional unit is defined, following some criteria as formulated by Kjaer et al. (2018). A qualitative judgement on the presence and size of rebound effects can also be added here, since quantifying rebound effect will generally be out of scope of a study.

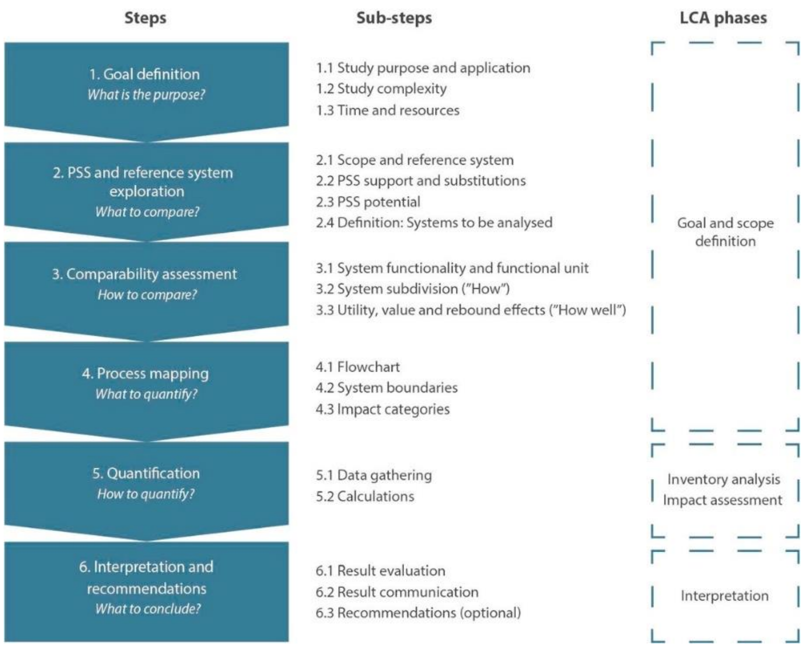

Figure 2: The guidelines as proposed by Kjaer et al., including the sub-steps and their link to the LCA phases (Kjaer et al., 2018, p. 669)

4. Process mapping. Step 4 deals with the flowcharts and the system boundaries. For PSSs, it is important that contributing services are not excluded, assuming they do not contribute significantly. Examples of such services are administration and capital goods like buildings.
5. Quantification. For this step, the ISO standards on the Life Cycle Inventory and the Life Cycle Impact Assessment phases can be followed.
6. Interpretation and recommendations. Kjaer et al. (2018) argue that this step should include three aspects: the avoided impacts, induced impacts and rebound effects.

4.4. Chapter summary and conclusion

This chapter's sub question is: *which challenges and problems could arise when modelling product-service systems through LCA and what ways are suggested to overcome these challenges?* An often mentioned challenge is the definition of the functional unit. Furthermore, the ex-ante nature of most LCAs on PSS increases uncertainty and can make it, for example, hard to determine the reference system to compare the PSS to. It is questionable whether such challenges are only challenges when modelling PSS through LCA or that these or LCA or modelling challenges in general. Two studies came up with guidelines to overcome the challenges: Dal Lago et al. (2017) and Kjaer et al. (2018). The guidelines of Dal Lago et al. (2017) were found to barely guide anyone towards conducting an LCA on a PSS. The guidelines of Kjaer et al. (2018) were followed and the result is included in Appendix B.

Chapter 5: LCA of the Gorenje washing machine – sales versus pay-per-wash

What are the environmental impacts per impact category of the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?

In this chapter, an LCA is conducted to quantify the environmental impacts of the Gorenje pay-per-wash model compared to a traditionally sold Gorenje washing machine. The alternatives are shortly referred to as the 'PPW model' or 'PPW' and 'sales model' or 'sales'. This chapter follows the prescribed LCA phases and the methodology of this chapter is discussed in section 5.1. The goal and scope are first defined in section 5.2, after which inventory analysis is presented in section 5.3. Section 5.4 deals with the impact assessment and section 5.5 presents the results in the interpretation phase. This chapter is summarised and the sub question is answered in section 5.6.

5.1. Methodology

Chapter 5 is a full LCA, from cradle-to-grave, including multiple impact categories. LCA's concepts and methodological steps are defined in ISO14040 standards (ISO, 2006). An LCA consists out of four phases: goal and scope definition, life cycle inventory analysis, impact assessment and interpretation. The goal and content of each phase are subsequently discussed below (ISO, 2006). In the first phase, the *goal and scope* of the LCA study are defined. The goal definition discusses the objective, the intended use of the study and its commissioners and target audience. The scope definition determines several scopes of the study, regarding the temporal, geographical and technological coverage and coverage of the economic processes. Lastly, the function, functional unit, alternative and reference flows are defined. In the *inventory analysis*, the product systems of the alternative and its flow diagrams are designed and the flow diagrams are made. The result of this phase is the inventory table that lists all elementary flows related to the chosen functional unit. In the third phase, the *impact assessment*, the results from the inventory table are characterised into impact categories such as climate change and eutrophication. The results are quantitatively expressed in a single unit that is typical for that impact category. The last phase is the *interpretation*. Here, a consistency and completeness check is performed and the results of the LCA are interpreted by for example contribution analyses and sensitivity analyses (Guinée et al., 2002).

These four phases were in practice accompanied by the LCA handbook (Guinée et al., 2002) and the guidelines by Kjaer et al. (2017). Kjaer et al. (2016, 2018) presented that performing an LCA on a PSS brings along some challenges that can be overcome by adding some additional steps to the standard LCA methodology. The discussion on this can be found in chapter 4. To deal with the challenges presented there, it was decided to elaborately discuss and follow the guidelines (Kjaer et al., 2017), see Appendix B.

The data collection of this LCA was initially set up around the data that Gorenje made available for this research. Ecoinvent 3.6 (Wernet et al., 2016) was used as a database and the life cycle was modelled in the Activity Browser software (Steubing et al., 2020). Details on the data collection and assumptions can be found in section 5.3.3 and Appendix C. Section 5.5.3 and section 5.5.4 show the results of contribution analyses and sensitivity analyses. The contribution analysis is performed by adding the functional flow of each process as functional unit in the Activity Browser. The sensitivity analyses are performed by altering some variables in the LCA model. These variables are listed in section 5.5.4.

5.2. Goal and scope definition

5.2.1. Goal definition

The goal of this study is twofold. First, it aims to compare a traditionally sold Gorenje washing machine with the Gorenje pay-per-wash model, to investigate whether the pay-per-wash model fulfils the expectation of reducing environmental impacts. Hotspots in the life cycles can be identified and some user scenarios will be examined and as a result, suggestions can be done to further optimise the model. Second, this research aims to add to the literature on quantifying PSS. Product-service systems, and pay-per-use models specifically, are expected to potentially reduce environmental impacts, but this is not often quantified and proven. Therefore, quantifications of PSS are called for.

This study is a graduation project for the Master Industrial Ecology (joint degree Leiden University and Delft University of Technology) and the second full LCA that is done by the student for educational purposes. Gorenje, a white goods company originating from Slovenia, is the commissioner/corporate client of this study. The student is supervised by Prof. Dr. Ir. C.A. Bakker and Dr. Ir. J.B. Guinée and they are assisted by L.T. Amatuni MSc. Mrs. Bakker is part of the ReCiPSS project (acronym of 'Resource-efficient Circular Product-Service Systems), a research project funded by the European Commission to support industry in achieving circular manufacturing systems and funding Gorenje among others. The target audience is, besides the supervisors, anyone interested within the Gorenje company or ReCiPSS project. Because the ReCiPSS project is still operating and the pay-per-wash model is still under development, all data used and presented in this study are strictly confidential and cannot be shared with others. A confidential appendix is provided to the supervisors only. This study is not a 'comparative assertion disclosed to the public', as defined in ISO14040 standards; so Gorenje cannot in any case claim environmental superiority of their products.

LCA is a common method to evaluate the environmental impacts over a product's lifecycle (Chen & Huang, 2019; Kjaer et al., 2016; Zhang et al., 2018). Different scenarios within an LCA can show how results vary, hence, it is a suitable tool to answer this conditional research question. A main characteristic of LCA is that it aims to assess the full life cycle of a product. This all-encompassing scope is a large strength, but besides a weakness, since it demands to simplify some aspects of a life cycle. Local impacts can usually not be included in an LCA. Furthermore, LCA is a static – as opposed to dynamic – way of modelling, and all processes are regarded as linear. LCA focuses on environmental impacts and as such neglects economic and social impacts. Lastly, every LCA requires some assumptions and normative judgements (Guinée et al, 2002). Although LCA aims to be rooted in science and standardisation by the ISO standards reduces its arbitrariness, researches and LCA consultants should be transparent about their assumptions and normative judgements.

5.2.2. Scope definition

This study is a cradle-to-grave LCA, which means that processes from the extraction of the materials until the end-of-life of the washing machine are included. This is an attributional LCA, which means that current demand and average processes and behaviour (as opposed to marginal processes and behaviour) are modelled.

The temporal coverage of the data is 2002 to 2019, where more recent data was preferred when available. The ecoinvent database sometimes extrapolates older data to the newer version of the database, resulting in outdated data. Usage of this type of data could not always be prevented. Data for this LCA was collected in September and October 2020.

The geographical coverage is Slovenia and the Netherlands. The washing machine is produced in Velenje, Slovenia. Some components for the washing machine are ordered from other countries, see Appendix C.1, section 1.1. The washing machine is assumed to be used in the Netherlands. For transport distances, the assumed town of residence of the household is Utrecht.

For the technology coverage, all technologies that are applied, such as injection moulding and steel extrusion, are taken from the ecoinvent database. Transport by lorry was assumed to have the EURO5 emission class.

The coverage of processes is production, use and end-of-life for the sales model and production, use, repair, refurbishment and end-of-life for the pay-per-wash model.

The selected midpoint impact categories are acidification, climate change, eutrophication, freshwater ecotoxicity, land use, photochemical oxidation, ozone layer depletion, resources: fossils and resources: minerals and metals and are all taken from the ILCD family (Fazio et al., 2018).

5.2.3. Function, functional unit, alternatives, reference flows

The function of the washing machine as assessed in this LCA is washing a household's laundry. The functional unit is set at 1 year of washing a household's laundry. In this study, there are two alternatives to wash a household's laundry: a traditionally sold Gorenje washing machine and a Gorenje pay-per-wash washing machine. The functional unit and the alternative taken together make up the reference flows:

- 1 year of washing a household's laundry in a traditionally sold Gorenje washing machine
- 1 year of washing a household's laundry in a Gorenje pay-per-wash washing machine

5.3. Inventory analysis

5.3.1. System boundaries

5.3.1.1. Economy-environment system boundary

This is a cradle-to-grave LCA and therefore the system includes all processes from the production of the washing machine to the end-of-life.

LCAs distinguish between environmental flows and economic flows. Environmental (elementary) flows are considered as such when they enter or leave the product system without human intervention. Emissions that occur directly to air and water are thus elementary flows. For some flows, it can be hard to determine if they are part of the economy or the environment, such as agricultural soil or water (Guinée et al., 2002). In this LCA, the treatment of wastewater belongs to the product system, following the LCA guidelines (Guinée et al., 2002), which state that only water that gets discarded to the environment after treatment can be considered an environmental flow. Also the waste streams in the end-of-life phase are economic processes, since these are done by humans and emissions occur from waste management processes.

5.3.1.2. Cut-off

Although LCA aims at including every single element of a product system in its model, there is a practical limit to doing so. There will thus always be some inputs or processes that were not possible to include in the LCA and become a cut-off (Guinée et al., 2002).

A first cut-off is the storage of the washing machine at a warehouse. After being produced in Velenje, Slovenia, the washing machine could be transported to Duiven, the Netherlands, before being sold to the consumer. No accurate data on the storing process was available within Gorenje.

Secondly, the standby and off-mode power consumption of the washing machine were not taken into account. It is known that the washing machine has a power consumption of 0.3 W when completely switched off and 0.7 W when in standby mode (ASKO, n.d.). Since the standby and off-mode power consumption would be the same for both alternatives, it was left out.

5.3.2. Flow charts

The flowcharts in figure 3 and 4 show the systems as modelled in the Activity Browser. Figure 3 presents the sales model and figure 4 presents the PPW model. A flow chart of the production of the washing machine is too big to include in this place and is included in Appendix D.

5.3.3. Data collection and relating data to unit processes

This LCA compares two alternatives: a Gorenje washing machine that is traditionally sold (hereafter shortly called “sales model” or “sales”) and the pay-per-wash washing machine (hereafter shortly called “pay-per-wash model” or “PPW”).

5.3.3.1. The sales model

The sales model is produced in Velenje, Slovenia and is assumed to be an ASKO W4086C type (ASKO, n.d.), although the data for the components comes from a slightly older model, following Volders et al. (2014), see also Appendix C, section data collection and section C.1.1. The washing machines consists out of more than forty components, - like side panels, the door, shock absorbers, the drum, electronics and packaging - weighs 75 kilograms and has a loading capacity of 8 kilograms. Over- and underloading is out of scope of this research: all laundry cycles are assumed to weigh 8 kilograms. All components of the washing machine are depicted in the production flow chart, figure D1 in Appendix D. The washing machine is transported in a 16-32 metric ton lorry, from Velenje to Utrecht (1250 kilometres).

In this baseline scenario, a household has bought[2] the washing machine and uses it 220 times per year (4.2 times per week). In this scenario, they only use the standard cotton programme at 40°C, since that programme and temperature are most frequently chosen by consumers (Schmitz & Stamminger, 2014). The standard cotton programme of the ASKO W4086C consumes 1.3 kWh electricity and 73 litres of water (ASKO, n.d.). The household is assumed to use 0.08 kilograms of detergent per laundry cycle (Amasawa et al., 2018; Volders et al., 2014). Over- and underdosing of detergent is out of scope of this research, just as ‘auto dose’ for detergent and the use of fabric enhancer.

[2] At the time of writing, the ASKO W4086C.S is in the Netherlands on sale for about 1,299.00 euros.

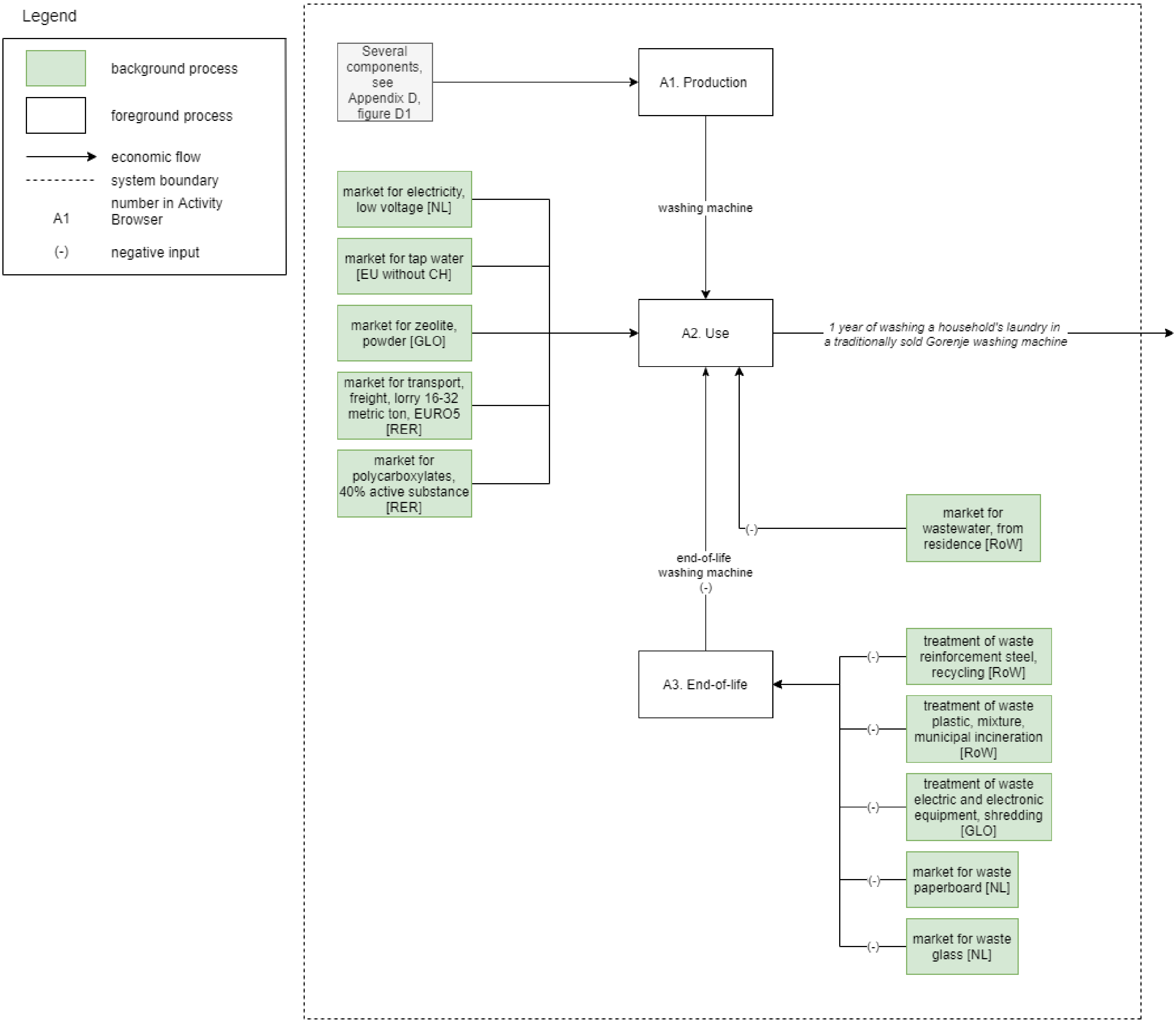

Figure 3: Flow chart of the sales model Gorenje washing machine

Washing machines reach their end-of-life on average after 12 years of use (Boldoczki et al., 2020; Tecchio et al., 2019). As will become apparent below, the ASKO W4086C type washing machine could easily last for 24 years or longer. However, it was decided to keep the lifetime of the sales model at 12 years, in line with the literature, since washing machines owned by consumers are not likely to reach their ultimate lifetime. Tecchio et al. (2019) found that although defective washing machines can often be repaired, consumers judge the costs of spare parts and labour as too high and decide to replace the defective washing machine with a new one (after 12.6 years on average). Furthermore, Tecchio et al. (2019) found that the average lifetime of a washing machine increased from 12.6 years when not repaired, to only 13.2 years when successfully repaired by a service engineer. More reasons on why washing machines in ownership by consumers reach their end-of-life after about 12 years can be found in Appendix C.

In the Netherlands, washing machines are collected at end-of-life and some parts are recycled. The washing machine is simplified to consist out of five waste streams 1) steel and cast iron, 2) plastics, Teflon and rubber, 3) e-waste, 4) packaging cardboard and 5) glass. The composition of the waste streams follows Volders et al. (2014), whose washing machine weighs 67 kilograms. The weight of the waste streams for the sales model are presented in table 6.

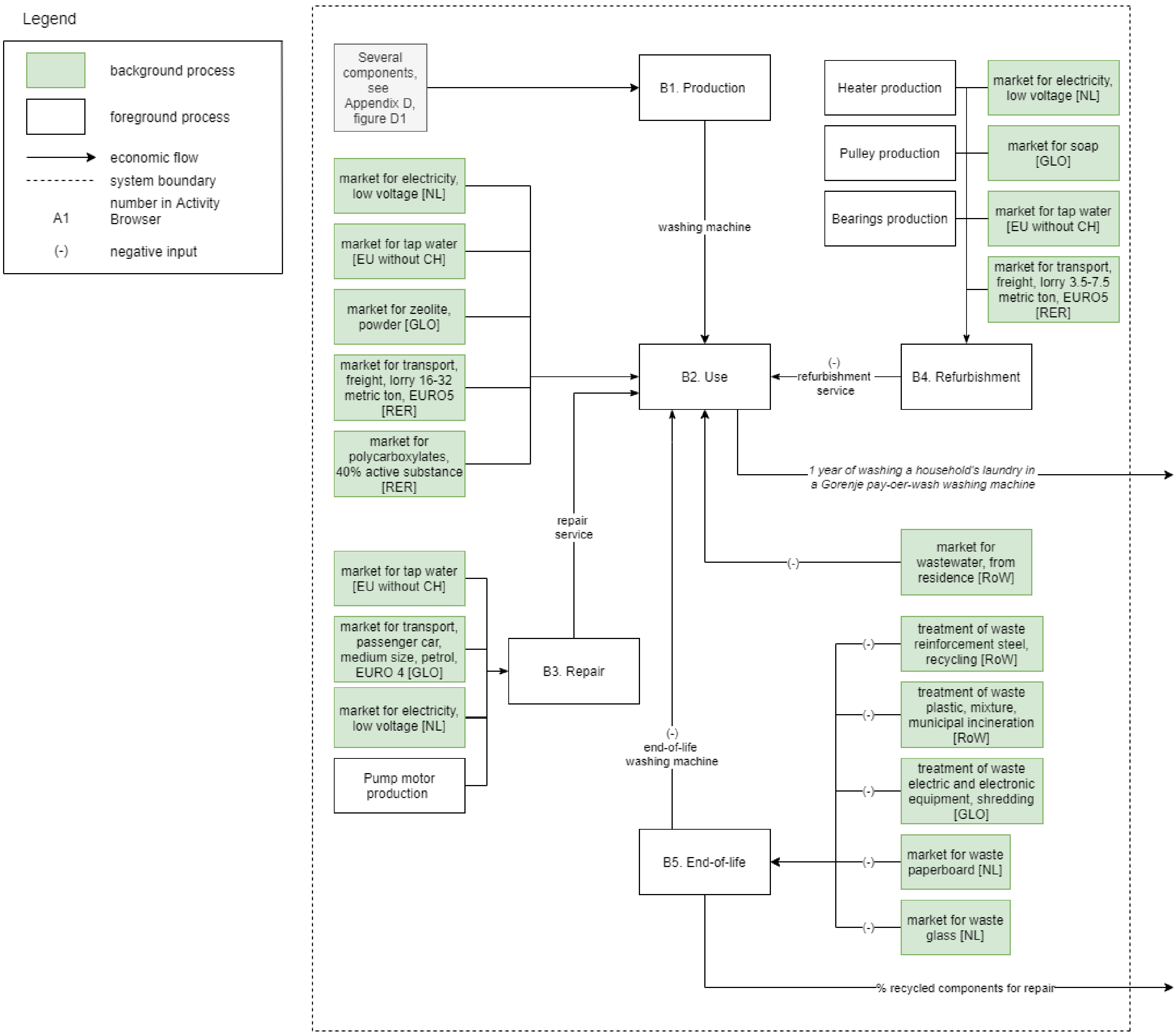

Figure 4: Flow chart of Gorenje's pay-per-wash model

5.3.3.2. The pay-per-wash model

The pay-per-wash model is in principle the same washing machine as would have been sold in a traditional business model. The model is produced in Velenje, Slovenia and is assumed to be an ASKO W4086C type (ASKO, n.d.). The main difference is that the PPW washing machine is Wi-Fi-enabled and has more advanced software than the sales model. This is needed to allow Gorenje to send the bills to its customers, as well as supporting them with tips how to wash more efficiently. The washing machine is transported in a 16-32 metric ton lorry, from Velenje to Utrecht (1250 kilometres) and is assumed to stay in the Netherlands for use, repair and refurbishment.

The use, repair, refurbishment and end-of-life phase of the pay-per-wash model are modelled ex-ante (i.e. before implementation). Although Gorenje has done some pilot projects and is extensively researching their options for the PPW model (also in the ReCiPSS project), no real data is yet available, which enlarges the uncertainty of the data and increases the number of assumptions for this part of the LCA.

In the baseline scenario, a household runs 220 laundry cycles per year (4.2 cycles per week) and pays a small fee per laundry cycle. The household enters into a contract with Gorenje for a set number of years. They can choose between a Gold subscription (contract duration 5 to 7 years, a new washing machine, moving service and instant software updates), a Silver subscription (contract duration 3 to 5 years, a washing machine as new and one software update per year) and a Bronze subscription (contract duration 1 to 3 years, a used washing machine and software updates on demand). For all subscriptions, Gorenje delivers, installs, repairs and collects the washing machine. In this baseline scenario, the assumed contract duration is 4 years. Gorenje expects to serve six customers per washing machine (A. Mihelič, personal communication, 21 October 2020). The lifetime of the PPW model is therefore set at 24 years (6 customers * 4 years). The household in this baseline scenario also only uses the standard cotton programme at 40°C (like in the sales model). The standard cotton programme of the ASKO W4086C consumes 1.3 kWh electricity and 73 litres of water (ASKO, n.d.).

The characteristics and assumptions of the alternatives as explained above are summarised in table 4.

In the repair process, a service engineer drives 50 kilometres to a customer (so 100 kilometres in total) in a passenger car, to repair a broken component of a customer's PPW washing machine. It is assumed that the service engineer repairs the pump motor, justifications for this assumption can be found in Appendix C. The service engineer runs a test cycle and leaves the customer. One repair service per 4 years is assumed - this can be regarded as a worst case scenario, see Appendix C.

In the refurbishment process, the washing machine is collected at the end of the contract duration and taken to the ATAG service centre in Duiven, the Netherlands. Since the washing machine is designed to last, Gorenje does not expect to refurbish many and major components (A. Mihelič, personal communication, 21 October 2020). The heater, pulley and bearings could require replacement after about 4,000 laundry cycles (A. Mihelič, internal communication/internal document, 27 October 2020). The washing machine is cleaned with cold water and soap and transported to the next customer within the Netherlands.

The characteristics and assumptions for the repair and refurbishment process of the PPW model are summarised in table 5.

Table 4: Characteristics and assumptions of the sales model and the pay-per-wash model

	Sales	PPW	Unit
Lifetime of washing machine	12	24	Years
Weight of electronics (main physical difference between washing machines)	0.90	0.93	kilograms
Number of laundry cycles per year	220	220	cycles
Contract duration	-	4	years
Washing temperature	40	40	°C
Washing programme	Standard cotton	Standard cotton	
Electricity use	1.3	1.3	kWh / cycle
Water use	73	73	liters / cycle
Detergent use	0.08	0.08	kg / cycle
Weight of loading	8	8	kg / cycle

When the washing machine has served six customers for four years, it reaches the end-of-life. The washing machine is simplified to consist out of five waste streams 1) steel and cast iron, 2) plastics, Teflon and rubber, 3) e-waste, 4) packaging cardboard and 5) glass. The composition of the waste streams follows Volders et al. (2014), whose washing machine weighs 67 kilograms. The numbers related to the end-of-life phase of the sales and PPW model are presented in table 6. These numbers are based on the weight of the washing machine (75 kilograms) and the lifetimes of the sales and PPW model.

All other assumptions, sources and considerations concerning the data of this LCA are included in Appendix C.

Table 5: Characteristics of the repair and refurbishment process in the PPW model

	Repair	Refurbishment
Transport	100 kilometres by passenger car	From Utrecht to Duiven (76 kilometres) by 3.5-7.5 metric ton lorry, and back (to another customer); 152 kilometres in total; 11.4 tkm
Repaired/replaced component	Pump motor	Heater, 0.5 bearings, 0.5 pulley
Electricity use	1.3 kWh	0.6 kWh
Water use	73 litres	30 litres
Soap use	-	0.2 kilograms

Table 6: Weight of the waste streams in the end-of-life phase, per functional unit

	Share	Sales	PPW	Unit
steel and cast iron	74.0%	4.625	2.313	kilograms
plastics, Teflon, rubbers	12.4%	0.775	0.388	kilograms
e-waste	11.3%	0.706	0.353	kilograms
packaging cardboard	0.4%	0.025	0.013	kilograms
glass	1.9%	0.119	0.059	kilograms

5.3.4. Results of inventory analysis

The result of the inventory analysis, the inventory table, can be found in the Excel Appendix.

5.4. Impact Assessment

5.4.1. Impact categories, characterisation models and factors, category indicators

An impact category combines multiple elementary flows to express those elementary flows in one category indicator result. The category indicator result is a result in a common unit specific for that impact category, such as kg SO_2 eq. for acidification and kg CO_2 eq. for climate change. The characterisation factor is a number that explains how much a specific elementary flow contributes to the impact category. For example, CO_2 and CH_4 both contribute to climate change (=impact category), however, the global warming potential (=characterisation factor) of CO_2 is 1 kg CO_2-eq/kg CO_2 and global warming potential (=characterisation factor) of CH_4 is 28 kg CO_2-eq/kg CH_4 (IPCC, 2014). The characterisation factors are the results of characterisation models that are composed by scientists and institutes.

All impact categories in this study come from the ILCD/PEF characterisation model. The midpoint impact categories are: acidification, climate change, eutrophication, freshwater ecotoxicity, land use, photochemical oxidation, ozone layer depletion, resources: fossils and resources: minerals and metals.

5.4.2. Characterisation results and discussion

Table 7: Characterisation results, per reference flow

Impact category	Sales	Pay-per-wash	Unit
Acidification	1.11	1.00	mol H+ eq.
Climate change	283.08	269.99	kg CO_2 eq.
Eutrophication	0.19	0.16	kg P Eq.
Freshwater ecotoxicity	318.96	281.73	CTU
Land use	1,737.57	1,662.81	Points
Photochemical ozone creation	0.66	0.60	kg NMVOC-
Ozone layer depletion	0.00	0.00	kg CFC-11
Resources: fossils	4,362.81	4,163.84	Megajoule
Resources: minerals and metals	0.02	0.01	kg Sb eq.

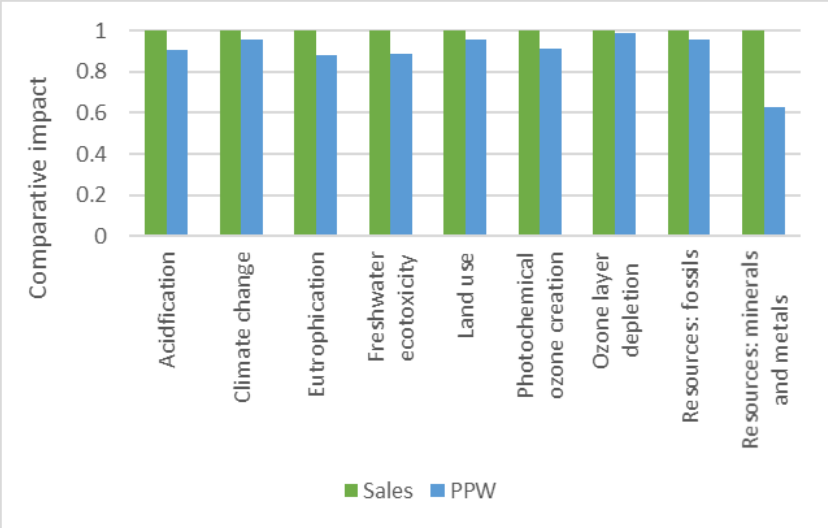

Figure 5: Comparative impact of the sales and PPW model

Table 7 shows the (rounded) indicator results per impact category and figure 5 shows the comparative impact of the two alternatives. Both present that the sales model has larger environmental impacts, for all impact categories. The difference between the two alternatives is relatively largest for resources: minerals and metals. For all other impact categories, the PPW model has at least 0.8 times the impact of the sales model.

5.5. Interpretation

5.5.1. Consistency check

This checklist is used to check whether the model and data matches the goal and scope of this study and to check whether choices and data are consistent between the two alternatives.

- Differences in data sources: both alternatives are based on the same data sources, namely primary sources, the bill of materials, information from Gorenje and the ecoinvent database. The production, use and end-of-life phase have no inconsistencies between the data sources for the two alternatives. The pay-per-wash model has two additional processes, repair and refurbishment, which is logically inconsistent since these are not present for the sales model.
- Differences in data accuracy: since both alternatives have the same data sources, there are no inconsistencies to report concerning data accuracy. The pay-per-wash model is modelled ex-ante, which increases the uncertainty (mostly for the repair and refurbishment processes). Data is thus less accurate for these processes since uncertainty is larger.
- Temporal differences and differences in data age: since all data sources are equal, there are no differences in data age or temporal issues.
- Differences in geographical representativeness: the washing machines are produced in Slovenia and then transported to the Netherlands for both alternatives. All locations are equal in both alternatives.
- Differences in the function performed: both alternatives perform the same function; washing a household's laundry. Only the business model in how they achieve this function is different: selling the complete washing machine as opposed to having the customer pay per laundry cycle.

5.5.2. Completeness check

This report is checked by L.T. Amatuni MSc and subsequently by Prof. Dr. Ir. C.A. Bakker and Dr. Ir. J.B. Guinée. The report is checked for confidentiality issues and errors by A. Mihelič from Gorenje. Their supervision has been aiming to prevent incompleteness of this study.

5.5.3. Contribution analysis

This section presents the contribution analysis in three ways. Firstly, figures 6 and 7 present the contribution analysis of life cycle stages of the sales and PPW model respectively. It shows how much each process in the life cycle contributes to the total environmental impact, per impact category. The stages are defined by the processes of the alternatives, so production, use and end-of-life for the sales model and production, use, repair, refurbishment and end-of-life for the PPW model. Afterwards, figures 8 and 9 present the contribution analysis by elementary flow and figures 10 and 11 the contribution analysis by process. By these analyses, a deeper understanding can be attained of which elementary flows and background processes contribute to the environmental impact per impact category.

Figure 6 and 7 demonstrate that the use phase contributes most to the environmental impact for both the sales and the PPW model. For the sales model, the use phase makes up more than 75% of the impact of resources: fossils, ozone layer depletion, land use and climate change. Noteworthy is the impact category resources: minerals and metals. Here, the production of the washing machine makes up 88% of the total environmental impact. The end-of-life phase of the sales model washing machine has a negligible effect on the total environmental impact.

The use phase is also the largest contributor for the PPW model, followed by the repair phase. The repair and refurbishment that are needed for the PPW model and the additional spare parts and transport that is coming along, contributes 11-42% for the repair phase and 3-11% for the refurbishment phase. Like in the sales model, the use phase contributes large shares to the impact categories resources: fossils, ozone layer depletion, land use and climate change. For the PPW model, also the impact category eutrophication is for 69% explained by the use phase. The production of the PPW washing machine contributes largely to the impact category resources: minerals and metals.

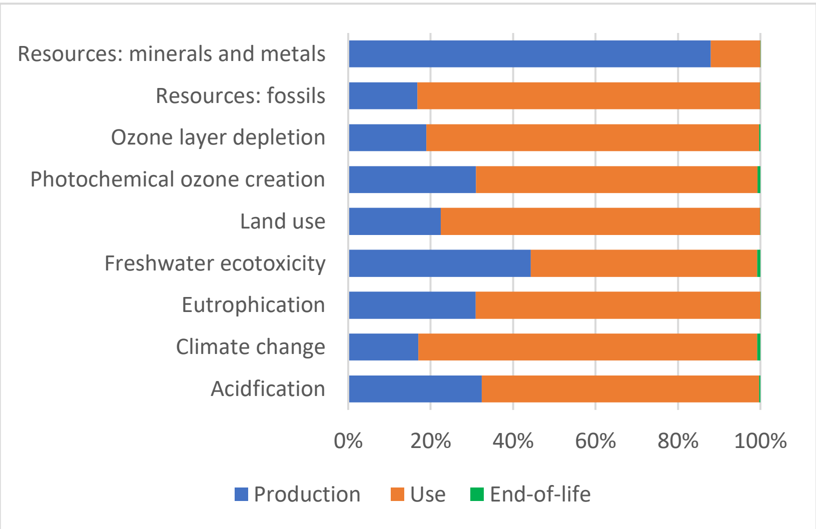

Figure 6: Life cycle stage contribution analysis of the sales model

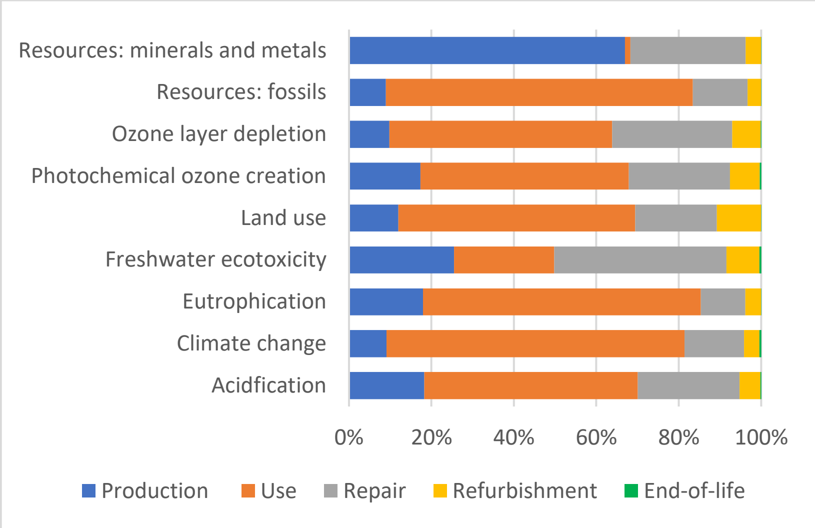

Figure 7: Life cycle stage contribution analysis of the PPW model

Figures 8 and 9 reveal which elementary flows contribute to the environmental impact per impact category. Acidification is for almost 60% caused by the emission sulphur dioxide, climate change for almost 90% by carbon dioxide and eutrophication for almost 100% by phosphate. Land use is mostly explained by intensive use of forest land, followed by mineral extraction sites and road networks. Furthermore, figures 8 and 9 present that the environmental impact of resources: minerals and metals is almost entirely (90%) caused by the extraction of gold and for almost 6% by the extraction of silver. Lastly, it should be noted that very minor differences are observed between the sales and PPW model in which elementary flows contribute to the environmental impact.

Figures 10 and 11 present which (background) processes contribute to the environmental impact per impact category. The main difference between the sales and PPW model here, is the contribution of 'road' and 'lead concentrate' to the PPW model, two process categories that are absent for the sales model. 'Road' contributes for almost 7% to the land use impact for the PPW model, which could potentially be explained by the additional transport from repair and refurbishment in the PPW model that is absent for the sales model. 'Lead concentrate' contributes for almost 7% to resources: minerals and metals for the PPW model and is not shown for the sales model. It is possible that this process contribution is also contributing to the environmental impact of the sales model, but in such a minor share that is grouped under 'rest'.

The environmental impact for climate change is for about 68% explained by electricity use and for about 10% by zeolite, which is a component of laundry detergent. Figures 6 and 7 already revealed the large contribution of the use phase for climate change and this additional information demonstrates that electricity use is the major contributing factor for this impact category. The extraction of resources: fossils is mostly explained by the contribution of hard coal (39%), followed by natural gas (23%), zeolite (9%), lignite (6%) and uranium ore (6%); and for the PPW model, by the contribution of petroleum (6%).

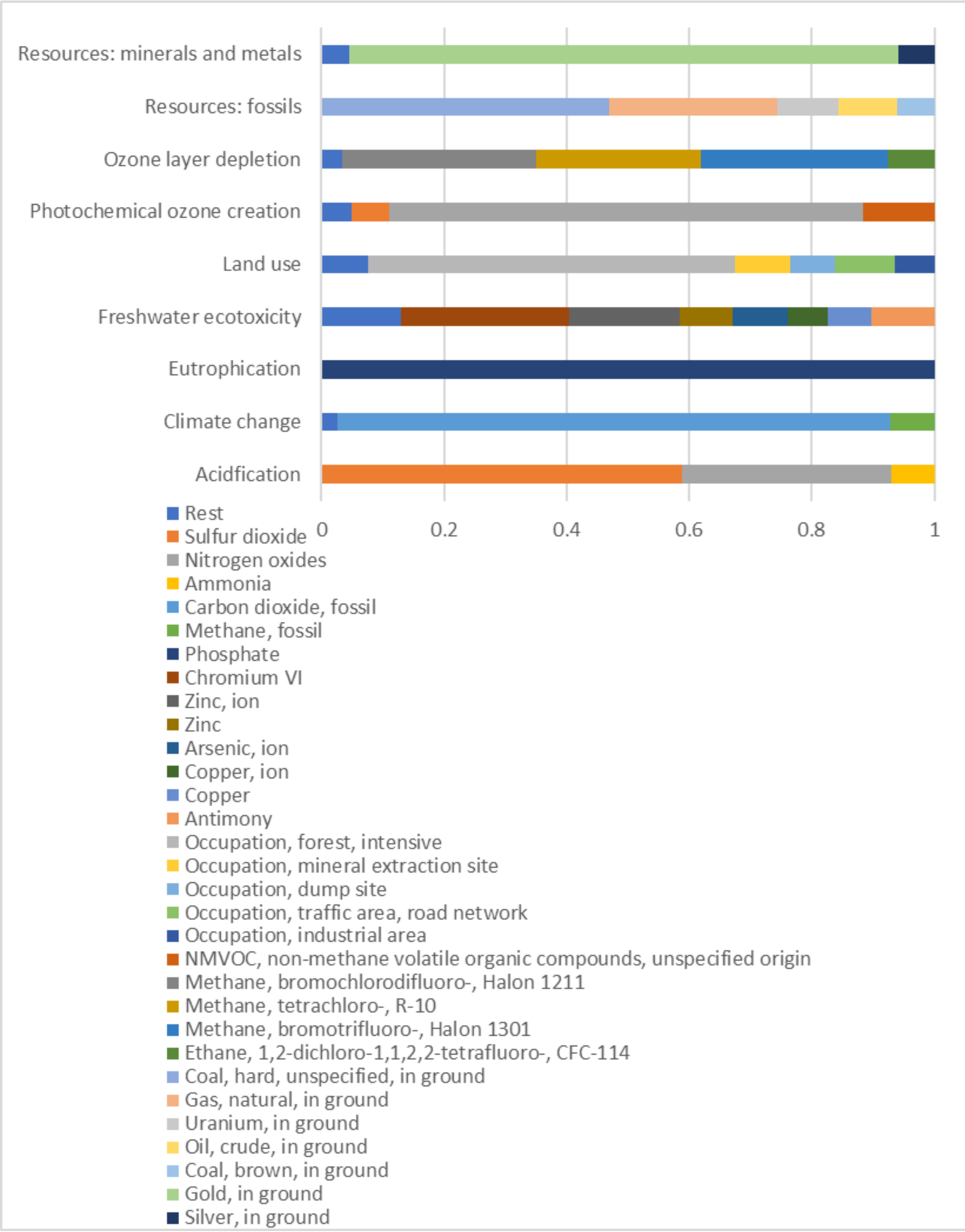

Figure 8: Contribution analysis by elementary flow of the sales model

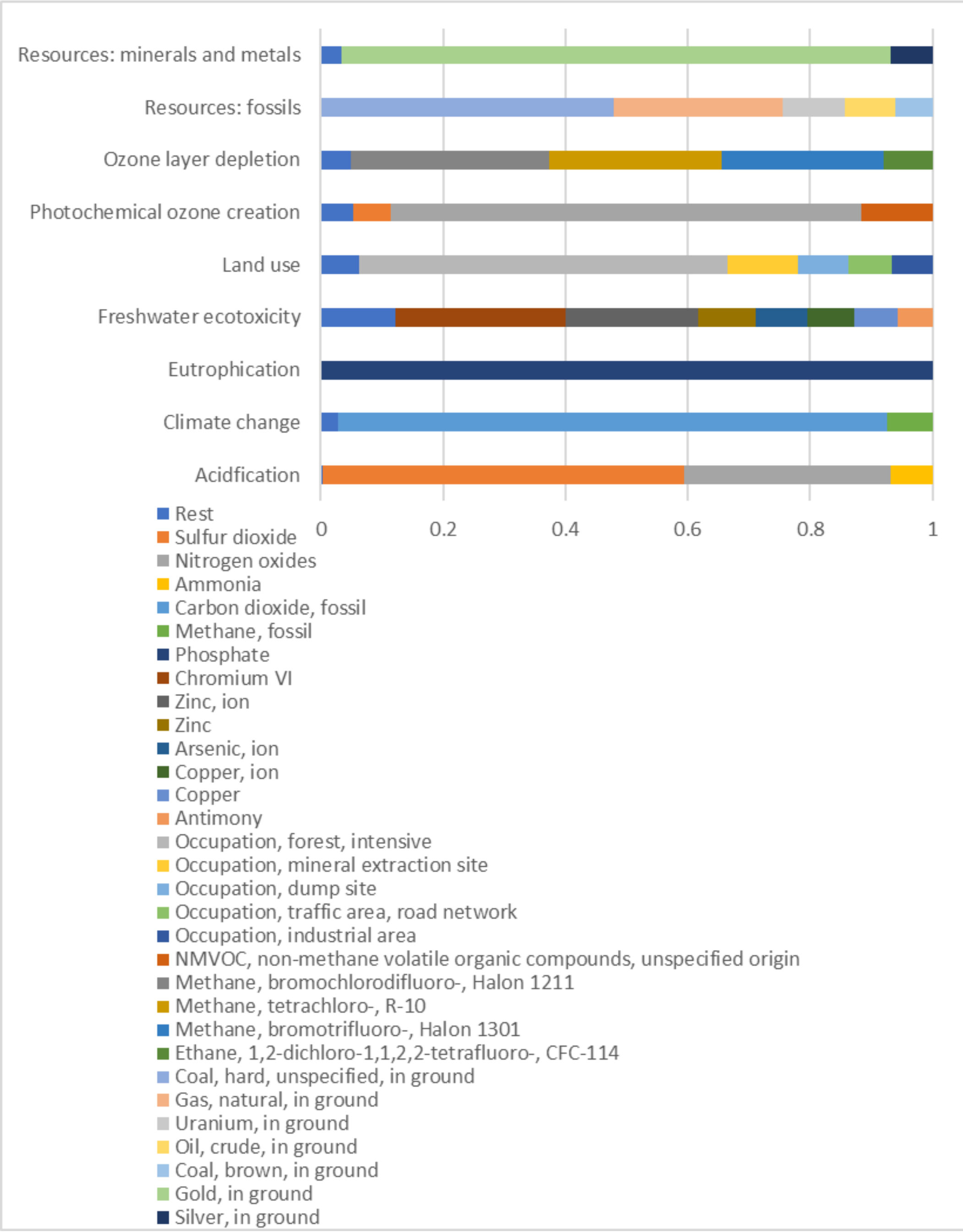

Figure 9: Contribution analysis by elementary flow of the PPW model

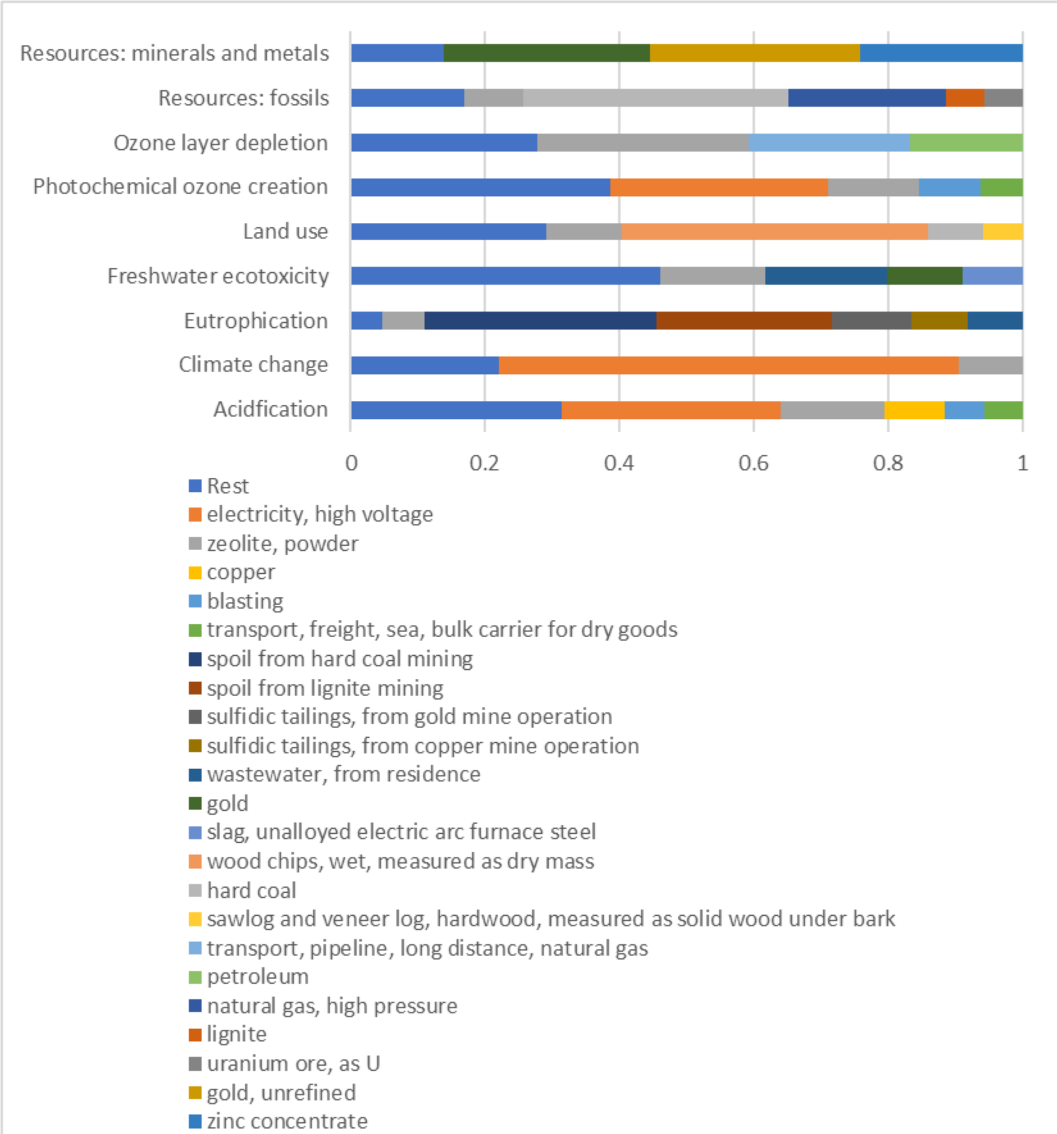

Figure 10: Contribution analysis of the sales model, by process, aggregated by reference product

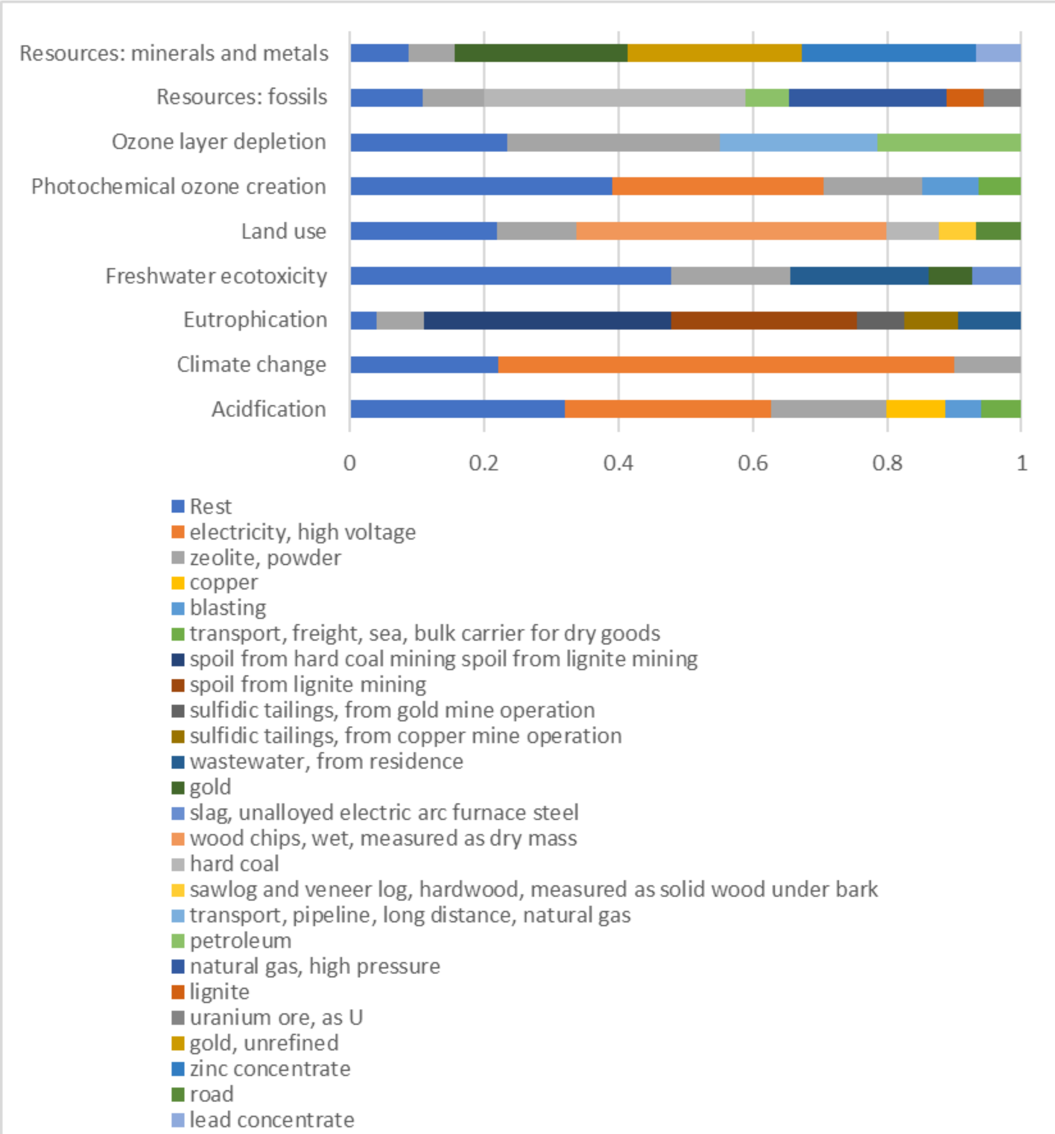

Figure 11: Contribution analysis of the PPW model, by process, aggregated by reference product

5.5.4. Sensitivity analyses

In order to be able to judge the robustness of the results, several sensitivity analyses are performed. In each sensitivity analysis, one variable or parameter is changed, while the others stay constant. The relative change (in percentages) in the outcomes shows how sensitive the model is to altering one variable. The variables that were chosen for these sensitivity analyses had either a relatively large contribution to the overall impact ('electronics' in sensitivity analyses 1 and 2 and 'electricity mix' in the use phase in sensitivity analyses 5 and 6) or were relatively uncertain because the author made choices that could have been made otherwise ('repair' in sensitivity analyses 3 and 4 and 'lifetime' in sensitivity analyses 7 and 8). The latter is also true for sensitivity analysis 9, which presents the outcomes using ReCiPe impact categories. Section 5.5.4.6 presents an analysis on some of the sensitivity analyses combined, to find out how changes in environmental impact from altered variables play out across the two alternatives.

5.5.4.1. Sensitivity analyses 1 and 2 – Electronics

In sensitivity analyses 1 and 2 (S1 and S2) the ecoinvent process for the electronics component is changed. Printed wiring boards are known to have a significant impact on the environment from a life cycle perspective (Bracquené et al., 2020) and there has not been as much advancement in the technology for printed wiring boards as compared to for example integrated circuits (Alcharaz Ochoa et al., 2019). Sensitivity analyses 1 and 2 are performed to test whether the model is sensitive to changes in the type of printed wiring board. The baseline scenario included a surface mounted printed wiring board (PWB), following Gorenje's bill of materials. The PWB in the sales model weighs 0.90 kilograms and consists out of the circuit board including software and a door lock. The PWB in the PPW model is heavier (0.93 kilograms), since it also includes a Wi-Fi module. In S1, the surface mounted PWB is replaced by a through-hole mounted PWB. S2 changes the PWB to 'electronics, for control unit', which has a composition of 46% steel (housing), 32% plastics, 14% printed wiring boards and 8% cables (various types) (Hischier, n.d.). Sir Asif (see Appendix C) advised to use this ecoinvent process, based on the LCA in Volders et al. (2014) (F. Asif, personal communication, 16 October 2020). Since the PWB is only 14% of the total weight of the 'electronics, for control unit', the weight of the PWB is smaller in S2 than in the baseline. Table 8 summarises the essence of S1 and S2.

Table 8: Alterations in the variable for the electronics component, in sensitivity analyses 1 and 2

Sensitivity	Alternative	Altered variable
Baseline	Sales	0.90 kg printed wiring board, surface mounted, unspecified, Pb free [GLO]
	PPW	0.93 kg printed wiring board, surface mounted, unspecified, Pb free [GLO]
S1	Sales	0.90 kg printed wiring board, through-hole mounted, unspecified, Pb free [GLO]
	PPW	0.93 kg printed wiring board, through-hole mounted, unspecified, Pb free [GLO]
S2	Sales	0.90 kg electronics production, for control units [RoW]
	PPW	0.93 kg electronics production, for control units [RoW]

Table 9 presents decreases in the outcomes for both S1 and S2, for both alternatives and across all impact categories. This implies that the type of PWB in the baseline scenario (i.e. surface mounted PWB) has a larger impact on the environment than a through-hole mounted PWB or an electronics component. The decreases are large for 'resources: minerals and metals', and substantial for eutrophication, freshwater ecotoxicity, photochemical oxidation and ozone layer depletion. Considering these substantial large decreases, the model can be considered quite sensitive to changes in the type of PWB.

Table 9: Results sensitivity analysis 1 and 2

	Change S1 compared to baseline		Change S2 compared to baseline	
Impact category	Sales	PPW	Sales	PPW
Acidification	-15.73%	-8.98%	-17.77%	-10.15%
Climate change	-8.04%	-4.35%	-9.16%	-4.96%
Eutrophication	-20.11%	-11.79%	-21.65%	-12.69%
Freshwater ecotoxicity	-20.00%	-11.70%	-21.27%	-12.44%
Land use	-10.44%	-5.64%	-11.82%	-6.38%
Photochemical ozone creation	-12.42%	-7.03%	-15.25%	-8.63%
Ozone layer depletion	-10.39%	-5.44%	-11.31%	-5.91%
Resources: fossils	-7.88%	-4.27%	-8.97%	-4.85%
Resources: minerals and metals	-68.25%	-56.30%	-72.55%	-59.84%

5.5.4.2. Sensitivity analyses 3 & 4 – Repair

In the baseline scenario, the service engineer replaces one pump motor in the repair service and the repair service is assumed to be required every 4 years. This is a worst case scenario, see also section 5.3.3, table 5 and Appendix C, since it is not likely that a washing machine needs a repair every 4 years. S3 therefore changes the repair service to one per 8 years. In S4, the repair service replaces the shock absorbers, instead of the pump motor. Table 10 summarises the essence of S3 and S4.

Table 10: Alterations in the variable for the repair phase, in sensitivity analyses 3 and 4

Sensitivity	Alternative	Altered variable
Baseline	Sales	Not applicable
	PPW	1 repair service per 4 years (is one customer/contract duration) Repaired component: pump motor
S3	Sales	Not applicable
	PPW	1 repair service per 8 years (per 2 customers/contract durations) Repaired component: pump motor
S4	Sales	Not applicable
	PPW	1 repair service per 4 years (is one customer/contract duration) Repaired component: shock absorbers

S3 in table 11 shows decreases in the outcomes between 1.36% and 5.22%, the model is thus sensitive to a change in the number of repair services that is done. Compared to S1 and S2, the sensitivity is substantially smaller. Even smaller than the decreases in S3, are the decreases in S4 (0.09% to 2.65%). The model is relatively unsensitive to a change in the type of component that is replaced in the repair service. S4 also demonstrates that the pump motor has a larger impact on the environment than the shock absorbers.

Table 11: Results sensitivity analysis 3 and 4

	Change S3 compared to baseline		Change S4 compared to baseline	
Impact category	Sales	PPW	Sales	PPW
Acidification	0.00%	-3.09%	0.00%	-2.32%
Climate change	0.00%	-1.81%	0.00%	-0.12%
Eutrophication	0.00%	-1.36%	0.00%	-1.39%
Freshwater ecotoxicity	0.00%	-5.22%	0.00%	-2.65%
Land use	0.00%	-2.47%	0.00%	-0.40%
Photochemical ozone creation	0.00%	-3.07%	0.00%	-0.77%
Ozone layer depletion	0.00%	-3.63%	0.00%	-0.09%
Resources: fossils	0.00%	-1.66%	0.00%	-0.09%
Resources: minerals and metals	0.00%	-3.78%	0.00%	-1.36%

5.5.4.3. Sensitivity analyses 5 & 6 – Electricity mix use phase

The Netherlands is the reference country of this LCA and therefore the average Dutch electricity mix was used in the baseline scenario. Other countries have different electricity mixes, with for example, more or less renewable energy. The Netherlands has always had a fossil-based (i.e. coal, oil and natural gas) electricity mix, while Germany has also used nuclear power and Slovenia's electricity mix has had almost equal shares fossils; nuclear; hydro (Dones et al., 2007). The ecoinvent data is based on statistics from 2016 (Treyer, n.d.a). The Dutch electricity mix then consisted mostly out of fossils (IEA, n.d.a.). In Germany, about 20% of the electricity mix consisted out of biowaste, wind, solar and nuclear energy in 2016 (IEA, n.d.b.). In Slovenia, about 20% originated from nuclear power and about 5% from hydro power (IEA, n.d.c.). S5 and S6 include the electricity mixes from Germany and Slovenia respectively, to see how sensitive the model is to changes in electricity source. Table 12 summarises the essence of S5 and S6.

Table 12: Alterations in the variable for electricity in the use phase, in sensitivity analyses 5 and 6

Sensitivity	Alternative	Altered variable
Baseline	Sales	286 kWh market for electricity, low voltage [NL]
	PPW	286 kWh market for electricity, low voltage [NL]
S5	Sales	286 kWh market for electricity, low voltage [DE]
	PPW	286 kWh market for electricity, low voltage [DE]
S6	Sales	286 kWh market for electricity, low voltage [SI]
	PPW	286 kWh market for electricity, low voltage [SI]

Table 13: Results sensitivity analysis 5 and 6

	Change S5 compared to baseline		Change S6 compared to baseline	
Impact category	Sales	PPW	Sales	PPW
Acidification	3.93%	4.34%	173.88%	192.24%
Climate change	-6.70%	-7.03%	-20.48%	-21.48%
Eutrophication	77.14%	87.52%	74.46%	84.49%
Freshwater ecotoxicity	2.37%	2.68%	6.23%	7.05%
Land use	-1.96%	-2.05%	-21.08%	-22.03%
Photochemical ozone creation	-9.20%	-10.07%	23.08%	25.29%
Ozone layer depletion	-11.52%	-11.66%	-8.94%	-9.05%
Resources: fossils	-4.17%	-4.37%	-7.09%	-7.43%
Resources: minerals and metals	3.72%	5.94%	0.09%	0.15%

Table 13 reveals that the model is very sensitive to changes in the electricity mix, however noting that this is more true for some impact categories than for others. Both S5 and S6 present large increases for 'eutrophication' which can be explained by the effect that nuclear power plants have on the water quality and aquatic ecosystems. The discharge of warm water reduces the solvation of oxygen, which impacts in turn the living species in the ecosystem (Clark, 2019; Poinssot et al., 2014). S6 shows that more nuclear energy causes a huge increase for acidification, while the smaller share of fossils compared to the baseline scenario substantially reduces the characterisation factors for climate change and resources: fossils.

5.5.4.4. Sensitivity analyses 7 & 8 – Lifetime

The baseline scenario assumed the lifetime of the sales model to be 12 years (see Appendix C, section 1.3), S7 assumes the lifetime of the sales model to be 10 years, following Bracquené et al. (2020). PPW model has a lifetime of 24 years in the baseline scenario, based on the contract duration of 4 years for six customers. As a result, the repair and refurbishment are also assumed to happen every 4 years. If the choice for the contract duration would have been made otherwise, to 6 years per customer (a Gold subscription, see section 5.3.3), the lifetime could be 36 years. This is tested in S8. Table 14 summarises the essence of S7 and S8.

Table 14: Alterations in the parameter for lifetime, in sensitivity analyses 7 and 8

Sensitivity	Alternative	Altered variable
Baseline	Sales	Lifetime: 12 years
	PPW	Lifetime: 24 years Repair: once per 4 years Refurbishment: once per 4 years
S7	Sales	Lifetime: 10 years
	PPW	Lifetime: 24 years
S8	Sales	Lifetime: 12 years
	PPW	Lifetime: 36 years Repair: once per 6 years Refurbishment: once per 6 years

Table 15: Results sensitivity analysis 7 and 8

	Change S7 compared to baseline		Change S8 compared to baseline	
Impact category	Sales	PPW	Sales	PPW
Acidification	6.64%	0.00%	0.00%	-8.72%
Climate change	3.65%	0.00%	0.00%	-4.76%
Eutrophication	6.20%	0.00%	0.00%	-7.23%
Freshwater ecotoxicity	9.22%	0.00%	0.00%	-12.99%
Land use	4.73%	0.00%	0.00%	-6.74%
Photochemical ozone creation	6.50%	0.00%	0.00%	-8.68%
Ozone layer depletion	4.11%	0.00%	0.00%	-6.54%
Resources: fossils	3.46%	0.00%	0.00%	-4.46%
Resources: minerals and metals	17.64%	0.00%	0.00%	-27.05%

Table 15 presents that alterations in the lifetime most heavily change the outcomes for freshwater ecotoxicity and resources: minerals and metals. S7 demonstrates that the model is quite sensitive to a lifetime change of 2 years, with increases ranging from 3.46% to 17.64%. S8 presents the same: the model is sensitive to changing the lifetime of the PPW model. Extending the contract duration per customer with 2 years, reduces the impact for all impact with 4.46% to 27.05%.

5.5.4.5. Sensitivity analyses 9 – ReCiPe impact categories

Sensitivity analysis 9 includes a different set of impact categories than the baseline scenario: ReCiPe impact categories. Similar results for both types of impact categories enhances the robustness of the results. Besides, the ReCiPe method includes several additional impact categories that the ILCD does not include, which could bring new insights to the table.

Table 16: Characterisation results sensitivity analysis 9, ReCiPe impact categories

Impact category	Sales	Pay-per-wash	Unit
Acidification	0.85	0.77	kg SO_2 eq.
Climate change	275.15	262.79	kg CO_2 eq.
Eutrophication	0.19	0.16	kg P eq.
Freshwater ecotoxicity	26.07	20.76	kg 1.4-DC
Human toxicity	176.88	146.99	kg 1.4-DC
Agricultural land occupation	15.62	14.66	m^2-year
Urban land occupation	1.86	1.88	m^2-year
Marine ecotoxicity	23.24	18.47	kg 1.4-DB
Photochemical oxidation	0.65	0.60	kg NMVOC-
Fossil depletion	86.87	83.46	kg oil eq.
Metal depletion	43.05	29.75	kg Fe eq.
Ozone depletion	0.00	0.00	kg CFC-11
Terrestrial ecotoxicity	0.03	0.05	kg 1.4-DC

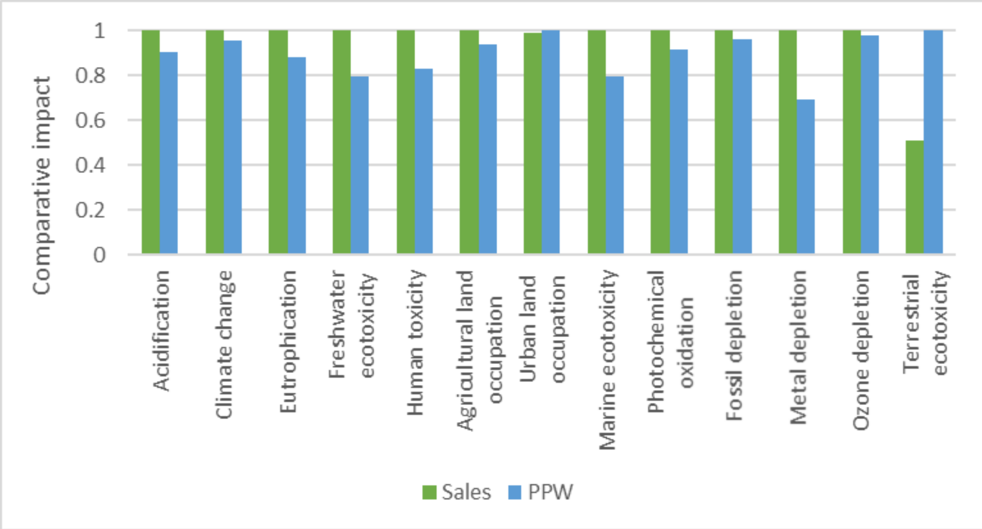

Figure 7: Results sensitivity analysis 9. Comparative impact per impact category

Table 16 shows that the sales model has a larger impact on the environment for almost all impact categories, except for urban land occupation and terrestrial ecotoxicity. The characterisation factors itself are hard to compare to the characterisation factors of table 7, because some impact categories have different units in the characterisation methods. Comparing the relative impact of the alternatives in figure 5 and 7, some things can be observed. The relative impacts for acidification, climate change, eutrophication, fossils depletion and photochemical oxidation are equal, which enhances the robustness of these results. Minor differences can be observed for freshwater ecotoxicity and metal depletion. The ILCD method included 'land use' as an impact category, but in the ReCiPe impact categories it appears that the PPW model has a larger impact than the sales model for urban land occupation and a smaller impact for agricultural land occupation. Terrestrial ecotoxicity was also not included in the ILCD method. S9 reveals that the PPW model has a substantially larger impact than the sales model for this impact category; something which would not have been known without this sensitivity analysis. Human toxicity and marine ecotoxicity were also not included in the ILCD method. S9 shows that the PPW model has a smaller impact for these impact categories: about 0.8 compared to the sales model.

5.5.4.6. Combined sensitivity analysis

Sensitivity analyses 1 up to 8 presented the results in percentual changes compared to the baseline scenario. As a consequence, the results do not reveal how alterations in the sensitivity analysis change the comparable impact of the alternatives. In order to say something about the environmental impact of some combined sensitivity analyses and their comparative impact across the two alternatives, a best case scenario and a worst case scenario are compared to the baseline. The weight of the electronics component, the repair of the PPW model and the lifetime of the sales and PPW model are considered in this combined sensitivity analysis. The results present the environmental impact of a certain scenario of combined sensitivity analyses across the two alternatives.

Table 17 presents the characteristics of the best case scenario, the baseline scenario and the worst case scenario. In the best case scenario, the weight of the electronics component is not increased for the PPW model and its lifetime can be extended to 36 years through customers' Gold subscription. The lifetime of the sales model is extended to 13 years, the maximum lifetime of a washing machine as reported in literature (Tecchio et al., 2019). In the worst case scenario, the electronics component and repair phase are not changed as compared to the baseline scenario, since these could already be considered as 'worst case' (see Appendix C). The lifetime of the sales model is limited to 10 years, in line with Bracquené et al. (2020), while the lifetime of the PPW model is limited to 12 years if customers choose a Bronze subscription.

Table 17: Alterations for the combined sensitivity analysis

	Alternative	Altered variables
Best case	Sales	▪ Electronics: 0.90 kilograms ▪ Repair: not applicable ▪ Lifetime: 13 years
	PPW	▪ Electronics: 0.90 kilograms ▪ Repair: one repair per 8 years; shock absorbers ▪ Lifetime: 36 years (6 customers * 6 years (Gold subscription)
Baseline	Sales	▪ Electronics: 0.90 kilograms ▪ Repair: not applicable ▪ Lifetime: 12 years
	PPW	▪ Electronics: 0.93 kilograms ▪ Repair: one repair per 4 years; pump motor ▪ Lifetime: 24 years (6 customers * 4 years (Silver subscription)
Worst case	Sales	▪ Electronics: 0.90 kilograms ▪ Repair: not applicable ▪ Lifetime: 10 years
	PPW	▪ Electronics: 0.93 kilograms ▪ Repair: one repair per 4 years; pump motor ▪ Lifetime: 12 years (6 customers * 2 years (Bronze subscription)

Figure 12 presents the results of the combined sensitivity analyses for five random impact categories, where the legend of the climate change impact category applies to all impact categories. Overall and unsurprisingly, the worst case scenario has the largest environmental impact, followed by the baseline scenario, which is followed up by the best case scenario. Furthermore, roughly two patterns can be observed here.

Firstly, for the impact categories climate change, land use and resources: fossils, the largest environmental impact is observed for the PPW model, worst case scenario. This is the only scenario in which the environmental impact of the PPW model is larger than the environmental impact of the sales model. This finding reveals the importance of the lifetime extension in the PPW model, since the only altered variable in this scenario compared to the baseline scenario, is the lifetime of the PPW model. If the PPW model does not succeed at extending the lifetime of a washing machine, it will most likely not reduce the environmental impact as compared to the sales model (at least for some impact categories).

Secondly, a different pattern is observed for the impact categories eutrophication and resources: minerals and metals. Here, the sales model has a larger environmental impact than the PPW model, across all scenarios. The PPW model thus has the potential to reduce the environmental impact as compared to the sales model within the worst case, baseline and best case scenario. However, it should be noted here that the PPW model in the worst case scenario presents a larger environmental impact than the sales model in the best case and baseline scenario. So, if the lifetime of the PPW model is limited to 12 years only, the environmental impact of the PPW model is not reduced as compared to the sales model under the assumptions made in the best case and baseline scenario.

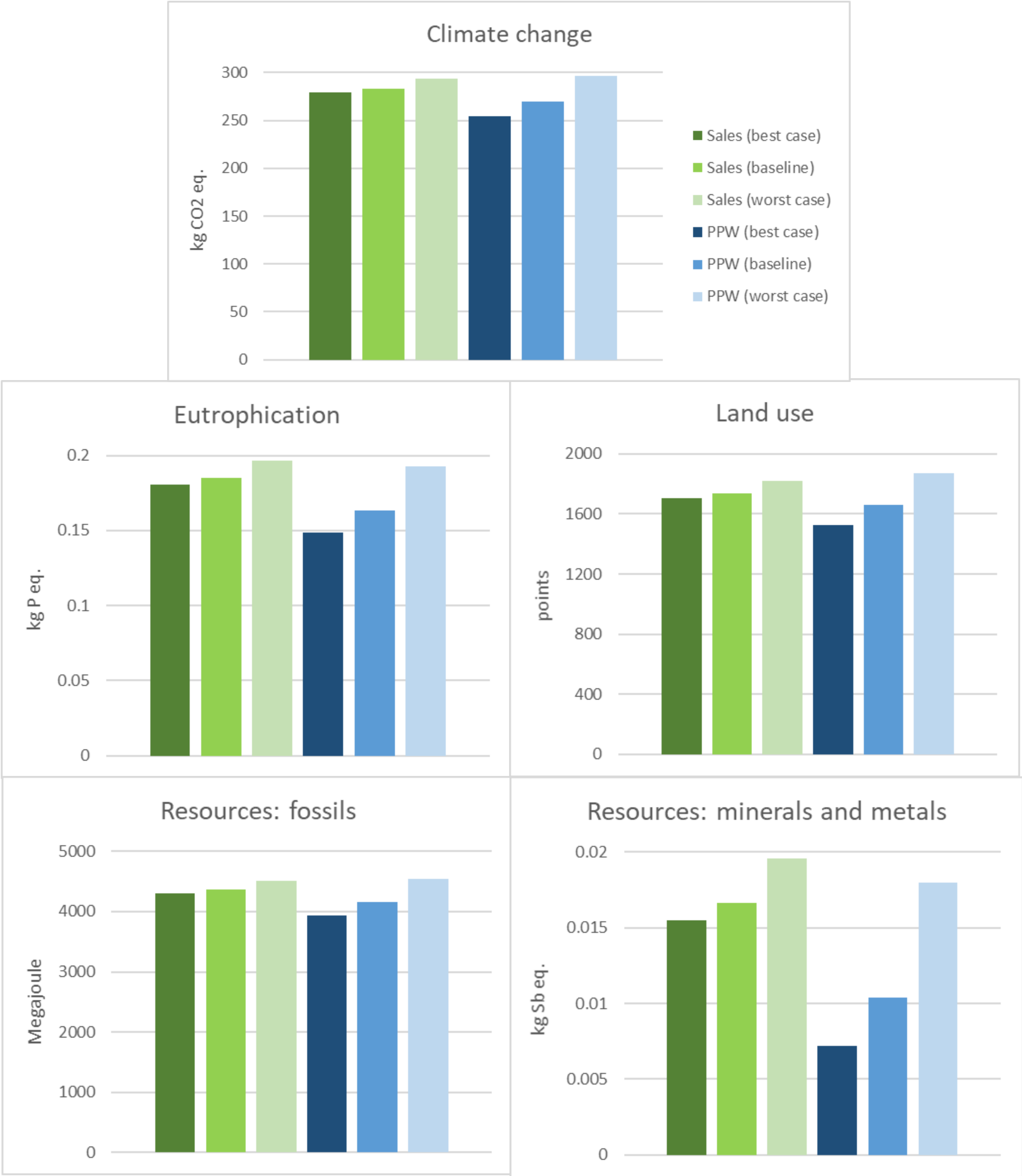

Figure 12: Results of the combined sensitivity analysis, for five random impact categories

5.6. Chapter summary and conclusion

Chapter 5 followed the LCA structure outlined by ISO14040 standards. The goal and scope were defined and the functional unit was set as '1 year of washing a household's laundry'. Two flowcharts have presented the modelled systems of the sales and PPW model and afterwards the assumptions of the modelled systems were discussed. Some of the main assumptions in this LCA are the lifetime of the sales model (12 years) and the PPW model (24 years). Furthermore, the PPW model needs Wi-Fi connection which is not required for the sales model and so, the printed wiring board of the PPW model weighs 0.93 kilograms instead of 0.9 kilograms. The PPW model comes with a repair service and is refurbished when a customer has used the washing machine for four years. These repair and refurbishment processes are modelled ex-ante and are therefore highly uncertain. The characteristics of these processes were presented in table 5.

This chapter aimed to answer the sub question: *what are the environmental impacts per impact category of the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?* The characterisation results in table 7 presented that the sales model has larger environmental impacts than the PPW model, for all impact categories. However, sensitivity analysis 9 showed that the PPW model has a larger environmental impact on urban land occupation and terrestrial ecotoxicity, when the ReCiPe method is applied. The difference between the two alternatives is relatively largest for resources: minerals and metals ('metal depletion' in the ReCiPe method). The environmental impact of this impact category is mostly explained by the production process: 88% for the sales model and 67% for the PPW model. Sensitivity analyses 1 and 2 showed that the model is very sensitive to changes in the type of electronics that is modelled, which means that the electronics component is influencing the outcomes notably. Sensitivity analysis 5 and 6 revealed the large influence of the electricity mix on the outcomes of the LCA. Increasing the lifetime of the PPW model – by extending the contract duration per customer – further reduces the environmental impact of the PPW model. The combined sensitivity analysis showed that if the PPW model does not succeed at extending the lifetime of a washing machine, it will not reduce the environmental impact for some impact categories.

Chapter 6: User types

How do several user scenarios change the outcome in environmental impacts related to the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?

This chapter presents the environmental impact of four user types with different characteristics. The methodology of this chapter is first described in section 6.1. To be able to describe the user types' characteristics, the literature is explored in section 6.2, after which the assumptions that underlie the user types are presented in section 6.3. Section 6.4 describes the user types and their characteristics. Section 6.5 presents the results of the analysis. Chapter 6 is summarised in section 6.6, which also answers the sub question.

6.1. Methodology

Chapter 6 is a scenario analysis within the LCA, where the same model is used as a starting point and only the use phase is changed. The analysed scenarios are four user types, called A, B, C and D. Since different persons can use their washing machines in very different ways – with the use phase being a large contributor to the environmental impact at the same time – it was decided to set up four user types with different characteristics.

To define the preferences of the user types, the literature was searched for characteristics and averages of certain groups. However, it was found that behavioural studies (on washing machine use and laundry behaviour) present averages without distinguishing between sub groups like youngsters, families, elderly or groups with certain concerns like the environment or hygiene. As a result, many assumptions needed to be made here. The assumptions are as much as possible based on literature. For inspiration and to provide assumptions as close to reality as possible, a study from Gorenje and work of Dr. Ir. S. S. (Sonja) van Dam were used. Sonja van Dam is also part of the ReCiPSS project, she is working at the TU Delft and she held a co-creation workshop with consumers, to discuss their laundry preferences, (dis)likes, habits and wishes (Van Dam et al., 2021). The 'personas' that resulted from this co-creation workshop are used for this research and quotes from people who were present at the workshop are included in the main text. The file with personas is included in the confidential Appendix.

6.2. Laundry behaviour

There are several studies that research the behaviour of consumers regarding their laundry and washing practices. To mention a few: Alborzi et al. (2017) study how socio-demographic factors affect the laundry behaviour in eleven European countries, Kruschwitz et al. (2014) investigate laundry practices in 236 households in Germany and Laitala et al. (2012) do the same in Norway in the years 2002, 2010 and 2011. Furthermore, Schmitz and Stamminger (2014) describe the results from a questionnaire on washing and drying behaviour of consumers in ten European countries.

But these studies have several limitations for the purpose of this chapter. Alborzi et al. (2017) and Schmitz and Stamminger (2014) do not include Dutch consumers in their studies. However, cultural differences affect how people in various countries do their laundry (Laitala et al., 2012). Also, the studies are slightly outdated and the questionnaires are often even held one or two years earlier, this is especially true for Laitala et al. (2012). Another limitation of these studies is that they present averages, which further complicates their usability to define user types for this chapter. To be able to root this chapter's user types in the scientific findings from the studies mentioned above, characteristics per user type are required. For example, one needs to know how often and at which temperature young individuals do their laundry *on average* (as a group) and how often and at which temperature families with two children do their laundry *on average* (as a group). The main problem with the studies presented above, is that they show *averages*, but no averages *per sub group*. This makes it impossible to distinguish factors that characterise certain sub groups, such as youngsters, families and eco-minded people. This complication is also found in Peruzzini et al. (2013), who perform an LCA on washing machines and include three user profiles: house manager, efficiency seeker and delegator. The user profiles are assumed to have a certain number of laundry cycles per week, but these are presented without argumentation or referencing.

So, the user types as presented in this chapter are as scientific as possible, but undisputable proof that this is the real consumer behaviour of these user types is unfortunately not on hand. The numbers as shown in section 6.4 and table 19 are estimated guesses. The user types were further restricted by the options that the ASKO washing machine has; the washing machine does not have a 90°C programme and only a limited number of 30°C programmes. Arguments for all the choices made are presented in Appendix E. The next paragraph presents a short overview of the main assumptions, as supported by the literature, that underlies the four user types.

6.3. Assumptions

Schmitz and Stamminger (2014) report that the average number of laundry cycles per person per week is 1.3. Kruschwitz et al. (2014) report that this number is slightly higher in Germany; 2.2 laundry cycles per week for a 1-person-household, 3.4 laundry cycles per week for a 2-person-household, 4.8 laundry cycles per week for a 3-person-household and 5.3 laundry cycles per week for a 4-person-household. The lower numbers from Schmitz and Stamminger (2014) are assumed for user type A and B and the higher numbers from Kruschwitz et al. (2014) are assumed for user type C and D.

Schmitz and Stamminger (2014) report that, on average, 40% of the laundry cycles is done at 40°C, 30% at 30°C and 30% at 60°C. Less than 5% of the laundry cycles is done at 90°C (Schmitz and Stamminger, 2014). This division is followed for the 'average household' user type C. User types A and B are assumed to wash at lower temperatures on average and user type D at higher temperatures on average.

Standard cotton is the most-used washing programme, followed by easy care, synthetics and wool/hand wash (Schmitz & Stamminger, 2014). This order is represented in the user types: user types B, C and D use standard cotton, user types A, B and C use the easy care programme and the other programmes are only used by two user types or less.

The electricity and water consumption of the washing programmes standard cotton (+ Eco), easy care, Eco 40-60, quick, hand wash and hygiene can be found in the washing machine manual (ASKO, n.d.).

6.4. Description of user types

This section describes the four user types. Each user type is supplemented with a quote from Dr. Ir. S. S. van Dam's 'personas', from a co-creation workshop that she did in the Netherlands and Slovenia (Van Dam et al., 2021). Hence, the quotes come from real people. Table 18 shortly introduces the user types A, B, C and D and their characteristics on doing the laundry. The user types are elaborately described below.

Table 18: Characteristics per user type, in short

User type A "Care-free YUP" ▪ Young, clothes are never very dirty, laundry should be quick, "do not really care" ▪ Washing at 30-40°C ▪ Low number of laundry cycles	**User type B "Eco conscious"** ▪ Eco-conscious, full loads, limited number of laundry cycles, eco-detergents ▪ Washing mostly at 30°C or colder ▪ Low number of laundry cycles
User type C "Multitasking fam" ▪ Family with (young) children, dirty clothes, washes at least 4 times a week ▪ Washing at 30 (sports), 40 (regular) and 60 (baby's clothes and bedding)°C ▪ High number of laundry cycles	**User type D "Germophobe"** ▪ Microbiologists, persons extremely caring about hygiene, concerned about bacteria ▪ Washing mostly at 60°C, or at least once a month ▪ High number of laundry cycles

6.4.1. User type A

User type A is the 'care-free Young Urban Professional (YUP)'. This person is young, lives alone and has a busy (social) life in which doing the laundry is not a priority. They consider their clothes as never being very dirty and since they live alone, they do not do the laundry very often. They do not really care about their laundry: it should be quick and easy. Characteristics of this user type are: low number of laundry cycles and washing at colder temperatures since warmer temperature cycles take too long.

> "*I prefer things simple, I would put everything together in one load. […] I do everything on 40°C and the short program for an hour... My clothes are not dirty."*
>
> *"There is a program called: quick. I have no idea how hot it is. Maybe it's 20, maybe it's 30. I put all my clothes that I have in there, and I just wash with that. For me it's fine."*

6.4.2. User type B

User type B is the 'eco-conscious person'. The assumed household consists out of two persons and they always do the laundry with care for the environment in mind. Therefore they never wash at 60°C, and if they would need to, they would choose the Eco 40-60 programme. They press the eco-option of the washing machine or they do a laundry cycle at a cold temperature. Characteristics of this user type are: low number of laundry cycles and washing at the lowest temperature possible.

"W*hat defines me is that I do eco-wash, wash at 30 degrees and I also try that I don't use fabric softener but I use vinegar and also to be very conscious about the environment."*

6.4.3. User type C

User type C is the 'multitasking family', having two young children and being very busy in general. The laundry is done multiple times per week and needs to fit into the busy schedule of the household. Having a baby brings along more laundry and the need to do some laundry cycles at 60°C. However, other laundry cycles can also be done at 30 or 40°C. Characteristics of this user type are: high number of laundry cycles and washing at various temperatures.

"We generally wash at 40°C, because it's not that dirty. […] For the children's clothes with puking stains we use this shout. We put it on and then we wash it at 60°C. I wash sport clothes at 30°C."

6.4.4. User type D

User type D is the 'germophobe', a person who is very concerned with bacteria. The household is assumed to consist out of two persons. They have knowledge in microbiology which makes them aware of bacteria or they are in another way generally concerned about bacteria and hygiene. For this reason they do the laundry more often and on higher temperatures than the average household. Characteristics of this user type are: high number of laundry cycles and washing at high temperatures.

"M*y sister is studying microbiology and she scared the shit out of me... There was a study that the bacteria that live in the washing machine can actually be harmful to you."*

"I use heavy chemicals. [...] I do most of my laundry at 95°C, only then all the spores are killed."

Table 19 below presents the characteristics of the user types in detail. For all user types, the three programmes that are most likely to be used are chosen (see Appendix E for justifications). Each user type has a division 40-30-30%, with 40% for the washing programme that is most often used, followed by the two other programmes. The related temperature, electricity and water use can be found in the manual of the washing machine (ASKO, n.d.). In this study, all user types are assumed to use 0.08 kg detergent per laundry cycle, since data on which sub groups are likely to over- or underdose are not on hand, and over- and underdosing of detergent is in general out of scope of this research.

6.5. Results

This section presents the results in two ways. First, it shows the environmental impact per user type for three random impact categories in absolute numbers. Then, it shows the comparative impact per impact category across the two alternatives for the four user types.

Figures 13, 14 and 15 demonstrate several things. First, from the four user types, user type C has the largest environmental impact for all impact categories. Since this user type also has the highest number of laundry cycles (because it has the largest household size), this does not come as a surprise. User type D has the second largest environmental impact and closely follows user type C in some impact categories like climate change and resources: minerals and metals. Noteworthy is the large difference in environmental impact between user type B and user type D; both have a household size of two persons, but user type D has a larger environmental impact for all impact categories and almost double the impact for climate change. Second, it can be observed that some impact categories are relatively largely determined by the user type and others are not. For climate change, the difference between the user type with the smallest impact (user type A) and the user type with the largest impact (user type C) is relatively large, while this is smaller for for example resources: minerals and metals. This is in line with figures 5 and 6 that show that some impact categories are for a larger share explained by the use phase than others. Thirdly, figures 13, 14 and 15 show the absolute difference in environmental impact between the sales and PPW model. Lastly, user type B has double the household size (2 persons) compared to user type A, but does not have double the impact. This could be due to the eco-mindedness of user type B, reducing their environmental impact.

Table 19: Characteristics per user type, all variables

	A	B	C	D
	Care-free "YUP"	Eco conscious	Multitasking fam	Germophobe
Household size (persons)	1	2	4	2
Number of laundry cycles per week	1.3	2.6	5.3	3.4
Number of laundry cycles per year	67.6	135.2	275.6	176.8
Washing programme(s)	- 40% Easy care (EC) - 30% Quick (Q) - 30% Hand wash (HW)	- 40% Standard cotton + Eco (SCE) - 30% Eco 40-60 (E) - 30% Quick (Q)	- 30% Standard cotton 60 (SC) - 40% Easy care (EC) - 30% Hand wash (HW)	- 40% Standard cotton 60 (SC) - 30% Easy care 40 C (EC) - 30% Hygiene (H)
Temperature	- 40% EC 40°C - 30% Q 20°C - 30% HW 30°C	- 40% SCE 40°C - 30% E 40-60°C - 30% Q 20°C	- 30% SC 60°C - 40% EC 40°C - 30% HW 30°C	- 40% SC 60°C - 30% EC 40°C - 30% H 60°C
Electricity use related to washing programme	- EC: 0.65 kWh - Q: 0.50 kWh - HW: 0.27 kWh	- SCE: 0.52 kWh - E: 0.84 kWh - Q: 0.50 kWh	- SC: 1.6 kWh - EC: 0.65 kWh - HW: 0.27 kWh	- SC: 1.6 kWh - EC: 0.65 kWh - H: 1.8 kWh
Water use related to washing programme	- EC: 60 litres - Q: 40 litres - HW: 58 litres	- SCE: 54 litres - E: 56 litres - Q: 40 litres	- SC: 75 litres - EC: 60 litres - HW: 58 litres	- SC: 75 litres - EC: 60 litres - H: 82 litres
Detergent use (kg / cycle)	0.08	0.08	0.08	0.08

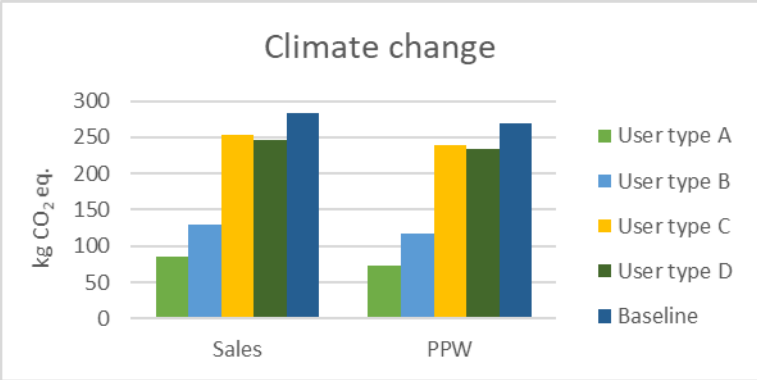

Figure 13: Environmental impact for climate change in kg CO2 eq., per reference flow

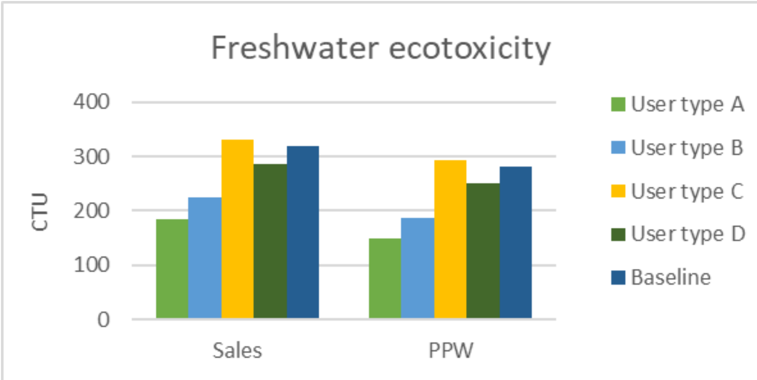

Figure 14: Environmental impact for freshwater ecotoxicity in CTU, per reference flow

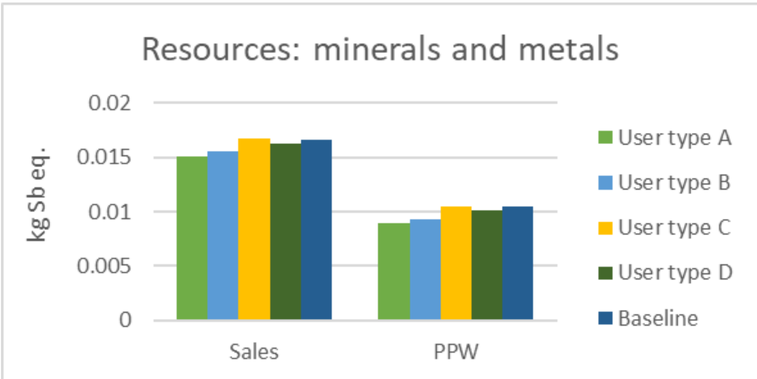

Figure 15: Environmental impact for resources: minerals and metals in kg Sb eq., per reference flow

Figure 16: Relative environmental impact per impact category, for user types A, B, C and D

Figure 16 presents the relative impact per impact category for the four user types. Like in the baseline scenario, resources: minerals and metals shows the largest difference in comparative impact between the sales and PPW model. Ozone layer depletion has the smallest difference in comparative impact. Furthermore, figure 16 demonstrates that user type A and B have larger differences in comparative impact than user type C and D. The smaller the total environmental impact for a user type is, the larger the difference in comparative impact. This can be explained by the large contribution of the use phase: if the use phase is larger (user type C and D), the reduced environmental impact of the PPW model is relatively smaller. This reduced environmental impact, consisting out of a longer lifetime for example, is spread over a larger total environmental impact due to the large contribution of the use phase. Note that there is no difference between the use phases of the sales and PPW model within a user type here; user type A is assumed to wash 67.6 washes per year in both the sales and PPW model. Consequently, these results do not mean that switching from a sales to a PPW model is more beneficial for user types A and B. That analysis will be performed in chapter 7.

6.6. Chapter summary and conclusion

Chapter 6 has introduced four user types, which reflect the distinct characteristics that different types of users can have. User type A is the 'care-free YUP', washing a low number of laundry cycles at 30-40°C. User type B is the 'eco conscious', washing a low number of laundry cycles, mostly at 30°C or colder. User type C is the 'multitasking fam', washing a high number of laundry cycles at various temperatures. User type D is the 'germophobe', washing a high number of laundry cycles at 40 or 60°C.

The results of the analysis presented that user type C has the largest environmental impact, closely followed by user type D. Chapter 6 aims to answer the sub question*: how do several user scenarios change the outcome in environmental impacts related to the Gorenje pay-per-wash model and a traditionally sold Gorenje washing machine?* This chapter showed that several user types can substantially change the outcome of the LCA, both for the sales model and the PPW model. Figures 13, 14 and 15 demonstrated that the baseline scenario has relatively high environmental impacts compared to the user types. User types A and B have evidently lower environmental impacts, user type D has somewhat lower environmental impacts and user type C can either be somewhat higher or lower, depending on the impact category. This shows that the type of user (and its behaviour) is an important factor in determining the environmental impact of the sales and PPW model. The variables that were changed in this analysis are number of laundry cycles per year, electricity use and water use, where the electricity use is based on the washing programme and the related washing temperature. The results have shown that customers' behaviour on these variables can change the impact of the sales and PPW model on the environment.

Chapter 7: User behaviour and rebound effects in the pay-per-wash model

What kind of user behaviour can be expected after the introduction of the pay-per-wash model and how would this behaviour change the outcome of the LCA?

This chapter discusses two types of user behaviour that users of the pay-per-wash model could uncover after they start using the pay-per-wash model. The first is related to the rebound effect, the second has to deal with the price incentive that is inherent to the pay-per-wash model. The methodology of this chapter is first presented in section 7.1. The rebound effect is then discussed in section 7.2. Afterwards, the study of Bocken et al. (2018) is discussed in section 7.3; that study will be referred to as the 'HOMIE paper'. Data from the HOMIE paper, on a Dutch start-up company introducing a pay-per-wash washing machine to the market, is used to discuss the second type of user behaviour. The price incentive – consisting out of a minimum amount per wash and a proportionally higher amount for laundry cycles at warmer temperatures – induces users to wash less often and at colder temperatures. Data from this paper is used to answer the second part of this chapter's sub question - *how would this behaviour change the outcome of the LCA?* - in section 7.4, which also summarises the first part of this chapter and answers the first part of this chapter's sub question.

7.1. Methodology

Chapter 7 uses the results from a paper (Bocken et al., 2018) to perform an analysis on how the results of the LCA could change if customers would wash less often and at lower temperatures, after introduction of the pay-per-wash model. To arrive at the end result, several steps had to be made, that are elaborately described below, illustrated by the example of user type C.

7.1.1. Step 1: Results from HOMIE case

The analysis of chapter 7 is based on data from the HOMIE case. HOMIE is a Dutch start-up and a spin-off of the TU Delft. The company introduced a pay-per-wash washing machine, in which laundry cycles at colder temperatures are cheaper for the customer than laundry cycles at warmer temperatures. The effects of the introduction of the pay-per-wash model with this pricing scheme on the number of laundry cycles and the average washing temperature are presented in Bocken et al. (2018). In month 1, participants use the washing machine in a regular way; that is, without a pay-per-wash model. In month 2, when participants pay per wash, Bocken et al. (2018) measure the effect on the number of laundry cycles and their average washing temperature (n = 56). A smaller sample size (n = 21) is followed for the duration of five months. The results are summarised in table 20 below. This table also includes the calculation of the average of month 3-5 and the decrease in percentages. Wherever in the remainder of this thesis 'n = 56' or 'n = 21' is written, this points back to the original data and sample size in Bocken et al. (2018).

Table 20: Number of laundry cycles per month as presented in Bocken et al. (2018) and the corresponding relative change per month in percentages

	n = 56		n = 21		
	Laundry cycles	Relative change	Laundry cycles	Average month 3-5	Relative change
Month 1 (without PPW)	12.9	-20.2%	15.2		-21.1%
Month 2	10.3		12		
Month 3			12.2	12.4	-18.4%
Month 4			12.1		
Month 5			12.9		

Table 21 and 22 summarise the results from Bocken et al. (2018) on the average temperature and adds the calculation of the average of month 3-5 and the relative change of the average temperature in percentages. Bocken et al. (2018) found a different effect for people who used to do the laundry at warmer temperatures than 40°C, as opposed to those who used to do the laundry at colder temperatures than 40°C. This distinction is also included in tables 2 and 3.

Table 21: Average temperature per month as represented in Bocken et al. (2018) and corresponding relative change per month in percentages, n = 56

	n = 56					
	Temperature	Relative change	Who used to wash >40°C	Relative change	Who used to wash <40°C	Relative change
Month 1 (without PPW)	40.2	-5.22%	45.6	-7.68%	34.8	-1.15%
Month 2	38.1		42.1		34.4	

Table 22: Average temperature per month as represented in Bocken et al. (2018) and corresponding relative change per month in percentages, n = 21

	n = 21								
	All, n = 21			Who used to wash >40°C			Who used to wash <40°C		
	Temp.	Average month 3-5	Relative change	Temp.	Average month 3-5	Relative change	Temp.	Average month 3-5	Relative change
Month 1 (without PPW)	39.8		-6.53%	46.2		-9.74%	33.4		-2.10%
Month 2	37.2			41.7			32.7		
Month 3	39.4	38.2	-4.02%	43.2	41.6	-9.96%	35.7	34.9	4.39%
Month 4	37.4			41.2			33.7		
Month 5	37.8			40.4			35.2		

7.1.2. Step 2: Calculating the number of laundry cycles

To calculate the number of laundry cycles per year after the introduction of the pay-per-wash model, two things are needed: the number of laundry cycles per year before the introduction of the pay-per-wash model and the increase/decrease in the number of laundry cycles per year. The number of laundry cycles per year (*row 1*) is divided by 12 to calculate the number of laundry cycles per month (*row 2*). The decrease in the first month is 20.2% (*row 3*, see table 20, n = 56) and the average decrease in the months thereafter is 18.4% (*row 4*, see table 20, n = 21). *Row 5* is *row 2* multiplied by *row 3*; while *row 6* is *row 2* multiplied by *row 4*. The total number of laundry cycles (*row 7*) is one time the number for month 1 plus eleven times the number for month 2-12.

Table 23: Calculation of total number of laundry cycles

		Baseline	A	B	C	D
1	Laundry cycles per year	220	67.6	135.2	275.6	176.8
2	Laundry cycles per month	18.3	5.6	11.3	23.0	14.7
3	Decrease month 1	-20.2%	-20.2%	-20.2%	-20.2%	-20.2%
4	Decrease month 2-12	-18.4%	-18.4%	-18.4%	-18.4%	-18.4%
5	Month 1	14.6	4.5	9.0	18.3	11.8
6	Month 2-12	15.0	4.6	9.2	18.7	12.0
7	Total laundry cycles	179.2	55.0	110.1	224.4	144.0

7.1.3. Step 3: Calculating the washing temperature

This process is repeated for the average temperature change, however, there are four different options since there is a distinction between those who used to wash <40°C and those who used to wash >40°C. The four different options are 1) average, n = 56; 2) average, n = 21; 3) distinction <40°C and >40°C, n = 56 and 4) distinction <40°C and >40°C, n = 21. For each of these four, a table like table 24 is computed. Table 24 shows the calculation of the average temperature for option 3) distinction <40°C and >40°C and n = 56 as an example.

Table 24: Calculation of new average temperature, when distinguishing between those who used to wash <40 and >40°C, where n = 56

	Baseline	A	B	C	D
Average temperature	40	31	37	43	54
Decrease month 1	-5.22%	-1.15%	-1.15%	-7.68%	-7.68%
Decrease month 2-12	-4.02%	4.39%	4.39%	-9.96%	-9.96%
Temperature month 1	30.9	30.6	36.6	39.7	49.9
Temperature month 2-12	38.4	32.4	38.6	38.7	48.6
Temperature	37.8	32.2	38.5	38.8	48.7

Average temperature of the user types are based on their washing temperature and washing programme as presented below (in section 6.4). For example, user type C washes 30% at 60°C, 40% at 40°C and 30% at 30°C. The average washing temperature of user type C is then 43°C ((0.3 * 60) + (0.4 * 40) + (0.3 * 30) = 43).

7.1.4. Step 4: Temperature based on washing programmes

The four scenarios as described in step 3 above, resulted in four different results for the average temperature after introduction of the pay-per-wash model. It was therefore decided to continue with the ‘best case scenario’ (lowest temperature) and the ‘worst case scenario’ (highest temperature).

To find the electricity and water use of the washing machine related to the average washing temperature of a consumer, assumptions on the washing programme that the consumer uses are needed. The three washing programmes that are assumed for the baseline scenario and the four user types are presented in table 19. User type C is here again used as an example: this user type washes with standard cotton at 60°C, with easy care at 40°C and a hand wash at 30°C. The best case scenario for user type C is 38.7°C and the worst case scenario is 41.2°C. The division in washing programmes for these temperatures are found in table 25 (calculation example: (0.15 * 60) + (0.42 * 40) + (0.43 * 30) = 38.7).

Table 25: Division in percentages for the washing programmes to meet the average washing temperature of 38.7°C and 41.2°C

User type C best case			User type C worst case		
Standard cotton 60	60°C	15%	Standard cotton 60	60°C	22%
Easy care	40°C	42%	Easy care	40°C	46%
Hand wash	30°C	43%	Hand wash	30°C	32%
		38.7			41.2

7.1.5. Step 5: Input of the model

The model requires the input of laundry cycles per year, the average electricity use per laundry cycle and the average water use per laundry cycle. The laundry cycles per year are calculated in table 23. Finally, the division in washing programmes leads to the calculation of the average electricity use and water use per laundry cycle. The ‘user type C best case scenario’ is presented in table 26 as an example. The electricity use is calculated as follows: (33.7 * 1.6 kWh) + (94.3 * 0.65 kWh) + (96.5 * 0.27 kWh) / 224.4 = 0.63. The water use is calculated in the same manner.

Table 26: Calculation of average electricity use per laundry cycle and average water use per laundry cycle for the ‘user type C, best case scenario’

Total laundry cycles	224.4					
Washing programme	Share	Laundry cycles	Electricity (kWh)	Water (litres)	Average electricity (kWh)	Average water (litres)
Standard cotton 60	15%	33.7	1.6	75	0.63	61.4
Easy care	42%	94.3	0.65	60		
Hand wash	43%	96.5	0.27	58		
		224.4				

7.2. The rebound effect

The definition of the rebound effect concept is debated in literature and agreement among scientists on one definition does not exist (Walnum et al., 2014). In general, the rebound effect concerns the effect that when cost reductions come with efficiency improvements, one could buy more of that improved product or other products or services (Thiesen et al., 2008). The concept is used within multiple disciplines that all have their own perspectives and specific assumptions (Walnum et al., 2014). Among these disciplines are energy economics, socio-psychology and industrial ecology. Industrial ecologists have used two terms for the concept: environmental rebound effect (ERE) and circular economy rebound (CER) (Warmington-Lundström and Laurenti, 2020). The ERE lays it focus on the environmental savings that would come from certain efficiency improvements, but are in practice never realised. In other words, in the environmental rebound effect there is a discrepancy between the expected and the actual environmental savings, because economic or behavioural mechanisms were not considered in the first place (Font Vivanco et al., 2016). The CER can occur in two ways: either the circular economy activities do not reduce the primary production of the product or the lower price of circular economy products shifts consumption to other activities and therefore increases consumption in order sectors (Zink & Geyer, 2017).

It is not inconceivable that such an effect would occur when people start using a pay-per-wash washing machine for the first time. The rebound effect like discussed above presupposes that a PPW model is cheaper than a sales model, which might not necessarily be the case. However, if a household saves money due to lower upfront investment costs for a washing machine or lower maintenance costs, they could spend the money saved on more environmentally harmful products or services. This behaviour also showed up in a study by Junnila et al. (2018), who found that reduced ownership at households does not automatically lead to reduced material footprint and carbon footprint. In that study, some households spent the money saved on other carbon-intensive services, for example on holiday travels. Other rebound effects are also imaginable, like the PPW model not reducing the primary production, since the long-lasting and Wi-Fi-enabled washing machines still need to be produced. Or a psychological rebound effect, when people think “my washing machine is already so environmentally friendly, I have done my part and will not change to an energy efficient fridge/electric car/second-hand clothes”, etcetera. Besides, several scientists pay attention to the rebound effect in the literature combining PSS and LCA as discussed in chapter 4, in which they warn that unforeseen behavioural effects could occur after the introduction of a product-service system (Dal Lago et al., 2017; Kjaer et al., 2016).

Rebound effects are difficult to quantify and so, not many studies do this. The literature on measuring rebound effects in the context of circular economy, product-service systems or sharing economy is even more limited (Warmington-Lundström & Laurenti, 2020). Makov and Font Vivanco (2018) were the first to measure rebound effects of reuse in the circular economy in their study on refurbished smartphones. They find an average rebound effect of 29%, with a range of 27-46% and for specific regions and consumer behaviours even higher than 100%, which is called the backfire effect. This means that at least a third, or maybe even all of the environmental savings could be diminished due to the rebound effect (Makov & Font Vivanco, 2018). Warmington-Lundström and Laurenti (2020) research the rebound effect for a boat sharing platform and find a rebound effect of about 20% for people who rent a boat, thus losing a fifth of the potential environmental benefits that the sharing platform brings along. Amatuni et al. (2020) study car-sharing platforms in the Netherlands, San

Francisco and Calgary and their potential to reduce life-cycle greenhouse gas emissions, while taking two types of rebound effects into account: the modal shift effect and lifetime shift effect. In their research, they find a more modest reduction in greenhouse gas emissions when they take these rebound effects into account. Previous studies predicted that car-sharing platforms could reduce greenhouse gas emissions with 67%, however, when rebound effects are taken into account, Amatuni et al. (2020) suppose that a car-sharing platform can only reduce emissions with 3% to 18%.

All in all, several studies show that rebound effects exist and that people could behave differently or unexpectedly in circular economy or sharing economy activities, diminishing environmental savings that were expected. Presumably, a rebound effect will occur for the pay-per-wash washing machine. This study cannot measure or proof the rebound effect for this case, as it is out of scope and a challenging job. Therefore, measuring the rebound effect for a pay-per-wash model remains a future task.

7.3. The price incentive in the HOMIE-case

7.3.1. Summary of the paper

The second type of user behaviour that is discussed in this chapter is user behaviour resulting from adding a price incentive to a pay-per-wash washing machine. Bocken et al. (2018) research what positive environmental impacts could come about after introduction of a pay-per-use business model, in this case also a pay-per-wash washing machine. They research this for the case of HOMIE, a Dutch company that offers a pay-per-wash washing machine. Customers only pay per wash – installation and maintenance is included – and the pricing scheme is encouraging customers to wash at lower temperatures (Bocken et al., 2018). A cold wash costs for example €1.13 and a wash at 90°C costs €1.69 (in 2017)[3].

Bocken et al. (2018) follow two samples of 56 and 21 customers to investigate whether their consumption patterns changed significantly after introduction of the pay-per-wash model. The sample of 56 customers is followed for two months and the sample of 21 customers is followed for five months, in which month 1 is taken as a reference, so without a pay-per-wash model. The results showed the following effect for average temperature and number of laundry cycles.

On average temperature, the full sample size significantly dropped their average washing temperature on average from 40.2°C before to 38.1°C after introduction of the pay-per-wash model. It was found that this effect was strongest among the group who used to wash at temperatures higher than 40°C. This group reduced the average washing temperature from 45.6°C to 42.1°C on average. The group who used to do the laundry at temperatures lower than 40°C on average, reduced the average washing temperature from 34.8°C to 34.4°C on average. To test whether this decrease in temperature resulted into a new habit, Bocken et al. (2018) followed the sample size of 21 customers over five months. The average washing temperature reduced after introduction of the pay-per-wash model and then remained stable (from 39.8°C, to 37.2°C, to 39.4°C, to 37.4°C, to 37.8°C). Again, the reduction in washing temperature was larger for those who used to wash at temperatures higher than 40°C (from 46.2°C, to 41.7°C, to 43.2°C, to 41.2°C, to 40.4°C). Those who already used to wash at relatively low

[3] More information can be found on https://www.homiepayperuse.com/

temperatures, did not significantly lower their average washing temperature, they even increased their temperature after month 2 (from 33.4°C, to 32.7°C, to 35.7°C, to 33.7°C, to 35.2°C).

For number of laundry cycles, the results also showed a significant reduction after introduction of the pay-per-wash model. For the full sample size, the number of laundry cycles declined from 12.9 to 10.3 cycles per month. Again, to discover if customers got accustomed to a new habit, 21 customers were followed for 5 months. A significant effect was found, with the average number of laundry cycles declining from 15.2, to 12.0, to 12.2, to 12.1, to 12.9.

For the remainder of this research, the term 'price incentive' will be used when talking about this type of pay-per-wash model, where a warmer wash is more expensive than a colder wash and the customer is in this way encouraged to more sustainable consumption.

7.3.2. Characteristics of the model after introduction of the price incentive

Section 7.3.2 discusses the main characteristics of the inputs of the model, that are used to derive the results in this chapter.

Table 27 shows the characteristics of the baseline scenarios and user types A-D, as they were in chapters 5 and 6. The inputs of the model in the Activity Browser are number of laundry cycles per year, electricity use per laundry cycle and water use per laundry cycle.

Table 27: Characteristics of the baseline scenario and user types A, B, C and D, as used in chapter 5 and 6

Before introduction pay-per-wash model					
	Baseline	A	B	C	D
Number of laundry cycles (per year)	220	67.6	135.2	275.6	176.8
Average temperature (°C)	40	31	37	43	54
Related electricity use (kWh)	1.3	0.49	0.61	0.82	1.38
Related water use (litres)	73	53.4	50.4	63.9	72.6

Table 28 presents the characteristics of the baseline scenario and user types A-D after introduction of the pay-per-wash model, when customers behave according the results from Bocken et al. (2018), so reducing their number of laundry cycles and average washing temperature. Since Bocken et al. (2018) distinguish between the full sample size, people who used to do the laundry <40°C and people who used to do the laundry >40°C, there are several options for the new average washing temperature (see the methodology section for an extensive description). From these options the 'best case scenario' (lowest average temperature) and 'worst case scenario' (highest average temperature) are chosen and continued with in this analysis, see table 28.

The number of laundry cycles, electricity use per laundry cycle and water use per laundry cycle as indicated in table 28 are inputs for the Activity Browser. The typologies of the user types are visible in table 28. For example, the eco-minded user type B has the lowest water use per laundry cycle and the germophobe user type D – washing at high temperatures – has (by far) the highest electricity use per laundry cycle. Note also that the number of laundry cycles, electricity use and water use per laundry cycle are all reduced as compared to table 27, because the customer now pays per wash and will wash less often and at lower temperatures (Bocken et al., 2018).

Table 28: Characteristics of the baseline scenario and user types A, B, C and D, after introduction of the pay-per-wash model, following the data from Bocken et al. (2018) when average number of laundry cycles and average washing temperature are reduced

	After introduction pay-per-wash model									
	Baseline		A		B		C		D	
	Best case	Worst case	Best case	Worst case	Best case	Worst case	Best case	Worst case	Best case	Worst case
Number of laundry cycles (per year)	179.2	179.2	55.0	55.0	110.1	110.1	224.4	224.4	144.0	144.0
Average temperature (°C)	38.3	38.4	29.7	32.2	35.4	38.5	38.7	41.2	48.6	51.8
Related electricity use (kWh)	0.86	0.86	0.47	0.49	0.58	0.60	0.63	0.74	1.09	1.27
Related water use (litres)	65.1	65.1	52.3	54.8	49.8	51.7	61.4	62.7	67.7	70.9

7.4. Results

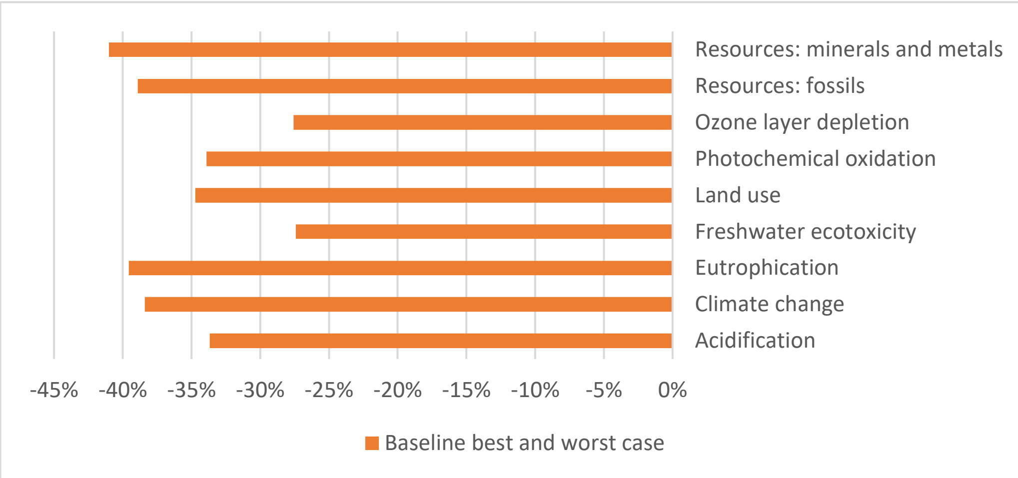

Figure 17: Change in environmental impact per impact category after introduction of the PPW model for the baseline scenario, compared to the baseline sales model.

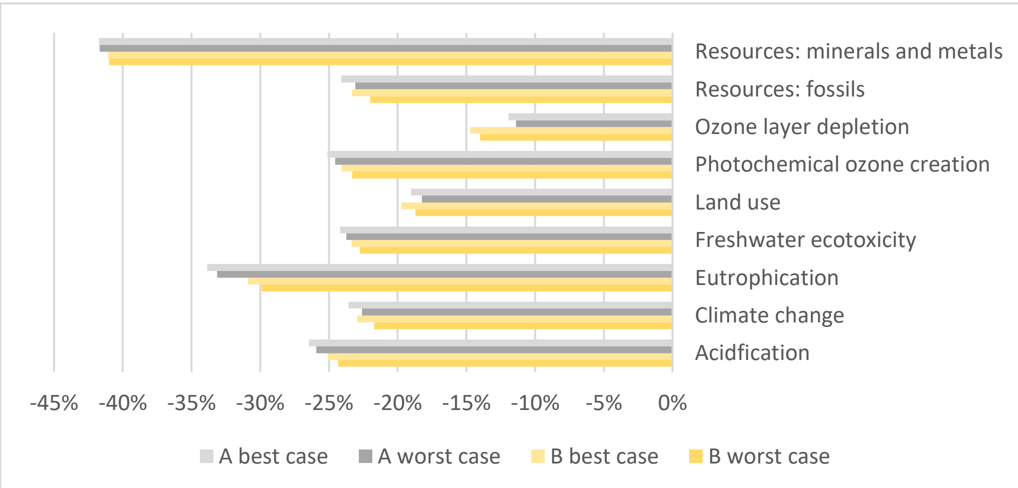

Figure 18: Change in environmental impact per impact category after introduction of the PPW model for user types A and B, compared to the sales model of user types A and B.

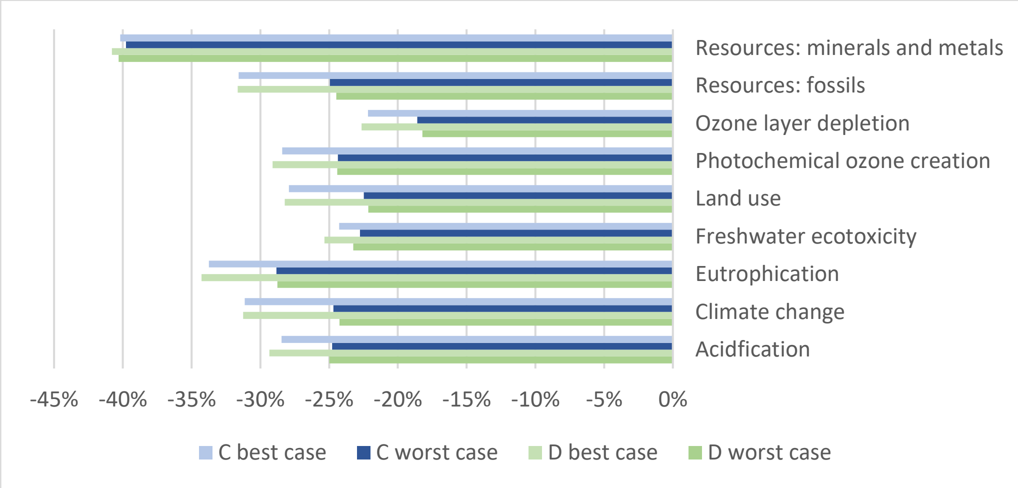

Figure 19: Change in environmental impact per impact category after introduction of the PPW model for user types C and D, compared to the sales model of user types C and D.

7.4.1. Results compared to the sales model

Figures 17, 18 and 19 above show the results of the analysis. The figures present the decrease as compared to the sales model in chapter 5 or 6. The decrease thus includes the effect of the longer lifetime of the PPW model (see chapter 5) as well as the effect of the changed behaviour due to the introduction of the pay-per-wash model (washing less often and at colder temperatures).

Figures 17, 18 and 19 demonstrate that the pay-per-wash model has the potential to reduce environmental impacts with up to 40% for some impact categories for all user types. Furthermore, the pay-per-wash model can reduce the environmental impact across all impact categories with at least 10%. In general, the introduction of a pay-per-wash model can reduce the impacts of 'resources: minerals and metals' most strongly, followed by eutrophication and acidification and for some user types; climate change. The results also show that the expected effects are slightly higher for the baseline scenario and user types C and D than for user types A and B. The baseline scenario and user types C and D have larger total environmental impacts and now appear to have relatively larger potential reductions.

7.4.2. Results compared to the PPW model

Figures 20, 21 and 22 below present the results when the model with the behavioural effects are compared to the PPW model of chapters 5 and 6. The decrease thus excludes the effects of the longer lifetime (because compared to the PPW model) and only includes the effect of the changed behaviour due to the introduction of the pay-per-wash model (washing less often and at colder temperatures). The x-axis is kept as ranging from -45% to 0%, to allow for easier comparisons with figure 17, 18 and 19.

Figure 20 shows that relatively large reductions in environmental impacts can be expected for the baseline scenario. Figures 21 and 22 reveal that the potential reduction in environmental impacts are smaller for user type A and B than for user type C and D. Since user types A and B already used to do their laundry <40°C, they are less likely to reduce their average washing temperature further after introduction of a pay-per-wash model, according to Bocken et al. (2018). This is represented in the results. However, still, the pay-per-wash model can reduce environmental impacts for user type A and B for all impact categories with about 5% to 10% (except for resources: minerals and metals). The potential reductions in environmental impacts due to behavioural change after introduction of a pay-per-wash model range from 10% to about 25% for user types C and D.

Comparing figures 17, 18 and 19 with figures 20, 21 and 22 several things stand out. First, the impact category 'resources: minerals and metals' had the largest reductions when compared to the sales model, but has the smallest reductions when compared to the PPW model. This implies that the environmental impact for this impact category can be reduced by switching from a sales to a PPW model, but is hardly reduced by the behaviour of the user. Second, the effect of the behavioural change is larger for user types that have a larger total environmental impact than for user types that already had a smaller environmental impact in general.

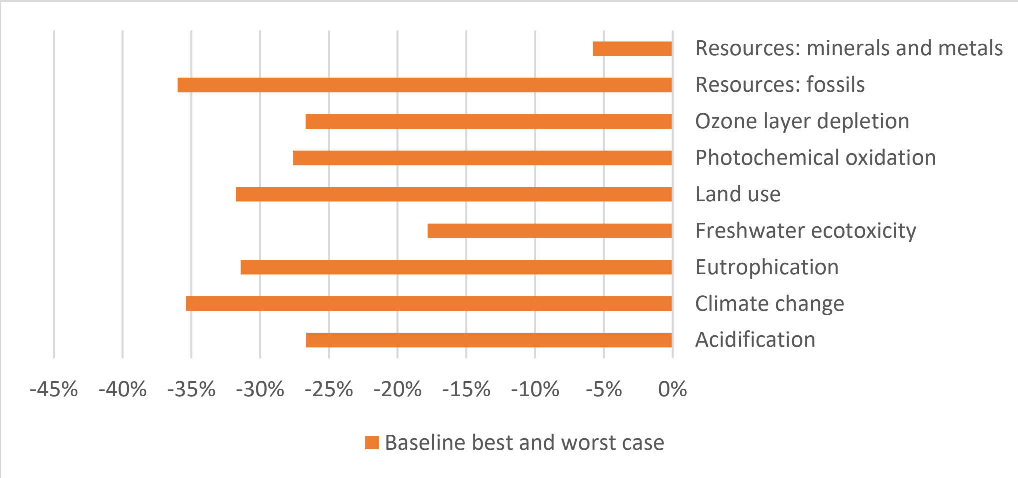

Figure 20: Change in environmental impact per impact category after introduction of the PPW model for the baseline scenario, compared to the baseline PPW model.

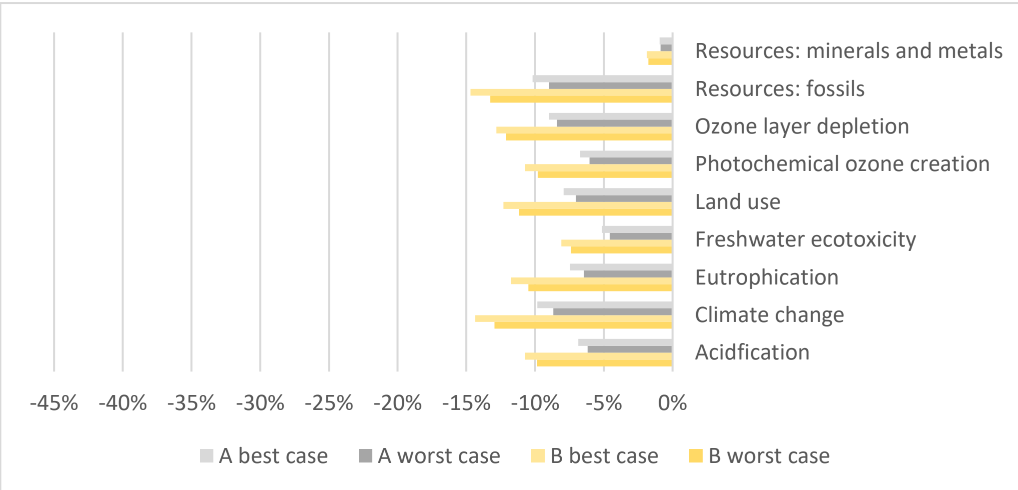

Figure 21: Change in environmental impact per impact category after introduction of the PPW model for user types A and B, compared to the PPW model of user types A and B.

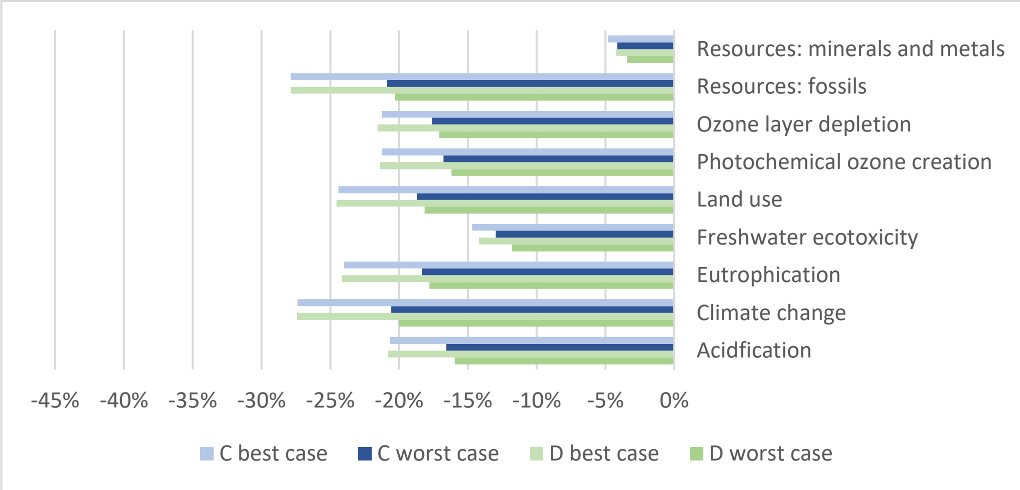

Figure 22: Change in environmental impact per impact category after introduction of the PPW model for user types C and D, compared to the PPW model of user types C and D.

7.5. Chapter summary and conclusion

Chapter 7 aimed to answer the following sub question: *what kind of user behaviour can be expected after the introduction of the pay-per-wash model and how would this behaviour change the outcome of the LCA?* Two effects were discussed to answer the first part of this question, namely the rebound effect and the effect of the price incentive that was presented in the HOMIE paper. The rebound effect could not be quantified in this thesis, but based on literature that has done such a quantification, it is not inconceivable that a rebound effect would occur when people start using a pay-per-wash washing machine. This could for example happen when a PPW model is cheaper than a sales model and a household spends the money saved on more environmentally harmful products or services. Moreover, the PPW might not reduce primary production, since the long-lasting and Wi-Fi-enabled washing machines still need to be produced. The second effect that can be expected after the introduction of the pay-per-wash model is the effect resulting from the price incentive that is included in the pay-per-wash model. Bocken et al. (2018) proofed that pay-per-wash models could achieve at lower number of laundry cycles and lower washing temperatures. The analysis included the baseline model and user types A, B, C and D and yielded the results as if the number of laundry cycles and washing temperature were lowered following the data from Bocken et al. (2018).

The results from that analysis answer the second part of this chapter's sub question, how behaviour could change the outcome of the LCA. It was shown that reducing the number of laundry cycles and lowering the washing temperature after introduction of a PPW model reduces the environmental impact for the baseline scenario and all user types, across all impact categories. Compared to the sales model, the PPW model can reduce environmental impacts with at least 10% and under some conditions, for some impact categories up to 40%. The baseline scenario and user types C and D show larger reductions in environmental impact than user types A and B. On average, the PPW model with the price incentive reduces environmental impacts with about 25% compared to the sales model. When comparing the results to the PPW models of chapter 5 and 6 it is found that environmental impacts can be reduced with about 5% to 10% for user types A and B and with about 10% to 25% for user types C and D and even slightly more for the baseline scenario (20%-25%).

Chapter 8: Optimalisation

How can the Gorenje pay-per-wash model be further optimised and which (behavioural) changes are needed to achieve this?

This chapter combines the lessons from the contribution and sensitivity analyses in chapter 5, the user types in chapter 6 and effects from the price incentive in chapter 7 to investigate what the most influential factors are in reducing the environmental impact of the pay-per-wash model. Combining these influential factors should deliver an 'optimal' PPW model, that is, having low characterisation results and/or large relative reductions compared to the sales model. This model will be called the optimal PPW model for the remainder of this chapter. Section 8.1 describes methodology of this chapter and section 8.2 describes the lessons that are drawn from chapter 5, 6 and 7 and which influential factors in the model could reduce the environmental impact of the PPW model. Section 8.3 shows how these influential factors are incorporated into the optimal PPW model and how the optimal PPW model differs from the baseline PPW model. Section 8.4 presents the results and section 8.5 summarises the chapter and answers the sub question.

8.1. Methodology

Chapter 8 combines the knowledge from chapters 5, 6 and 7 to investigate how the model can be further optimised. The influential factors are determined based on the results. From chapter 5 this is observed through the percentages in the contribution and sensitivity analysis. From chapter 6 this is based on the characteristics of the user types. The influential factor from chapter 7 is the price incentive that was analysed in that chapter. The influential factors are combined into the optimised model and are the input for the model in the Activity Browser. These results are compared to the results from the sales and PPW model in chapter 5.

8.2. Influential factors

8.2.1. Influential factors from chapter 5

The contribution analysis in chapter 5 showed that the use phase contributes most to the total environmental impact. So, reducing the influential factors from the use phase can potentially lead to largest reductions. The large contribution from the use phase is followed by the repair process, which contributes more to the total environmental impact than the production process for almost all impact categories. The production process contributes 67% to the total impact of resources: minerals and metals. Reducing the total environmental impact of this impact category is thus best done by focusing on the influential factors in the production process. For all other impact categories, influential factors should be found in the use phase and repair process.

Sensitivity analyses 1 and 2 showed that the model is very sensitive to changes in the type of electronics that is applied in the washing machine. Changes were especially large for the impact category resources: minerals and metals, ranging from 56% to 72%. Combining this knowledge with the above, suggests that the electronics component of the washing machine is an influential factor in reducing the environmental impact of the resources: minerals and metals impact category and an influential factor in the production process.

Sensitivity analyses 5 and 6 presented that the model is very sensitive to changes in the electricity mix, which suggests that this is an influential factor from the use phase. It should be noted that an electricity mix with more nuclear energy increases the environmental impact for eutrophication and acidification. An electricity mix with more renewable energy could reduce the impact for more impact categories.

A last lesson that can be learnt from chapter 5 is the impact of the lifetime of the PPW model. The lifetime is now based on Gorenje's assumption to serve six customers with one washing machine. The average contract duration of customers is still unknown, but if this could be extended to 6 or 7 years per customer, the environmental impact for all impact categories is reduced.

8.2.2. Influential factors from chapter 6

Chapter 6 introduced four user types and unsurprisingly, user type A and B had the lowest environmental impact. Moreover, user types A and B also showed the largest difference in comparative impact between the sales and PPW model. This revealed the large contribution from the use phase once more, since the use phases of user type C and D more or less diminish the positive environmental impacts from switching from a sales to a PPW model. Chapter 5 taught us that the use phase is the largest contributor; chapter 6 can now teach us which characteristics of user type A and B lead to their low environmental impact. Firstly, both user types had a number of laundry cycles which was taken from the literature and was 'on the low side', or in other words: other sources presented higher averages. Secondly, they did not run any laundry cycles at 60°C and as a result, their average electricity use per laundry cycle was low. User type A uses 0.49 kWh per laundry cycle on average and user type B 0.61 kWh per laundry cycle on average. Thirdly, user type B's care for the environment is reflected in its average water use, being the lowest of the four user types with 50.4 litres per laundry cycle. Influential factors to reduce the total environmental impact are thus number of laundry cycles, washing temperature and related electricity use and water use.

8.2.3. Influential factors from chapter 7

In chapter 7, the effects of the price incentive that are presented in the HOMIE paper, were applied to the LCA model. From these results, two influential factors that could reduce the total environmental impact of the PPW model are found. Firstly, adding a price incentive to the PPW model reduces the impact for all impact categories. These reductions are larger for the baseline scenario and user type C and D, because they used to wash at average temperatures >40°C and Bocken et al. (2018) found that temperature reductions are larger among those groups, compared to those who used to wash at average temperatures <40°C. A price incentive in the PPW model is thus an influential factor to reduce the environmental impact, especially for those who used to wash at warmer temperatures. Secondly, chapter 7 showed once more that the impact category resources: minerals and metals is not influenced by behaviour of the customer. The influential factor to reduce this impact category should thus be looked for in the production phase or in the lifetime of the washing machine.

8.3. The optimal PPW model

The influential factors from section 8.2 are converted into changes in the PPW model, to design a more optimal PPW model. This optimal PPW model is analysed in the LCA, to investigate how much all the influential factors combined, reduce the total environmental impact. Table 29 shows a comprehensive list of all the changes made and the characteristics of the optimal PPW model. They are elaborately discussed and justified below. In table 29, the third column presents the assumptions as they were in the baseline PPW model (in chapter 5), the fourth column presents the assumptions for the optimal PPW model as identified in this chapter.

Table 29: Characteristics of the optimal PPW model, as compared to the baseline PPW model

Life cycle phase	Variable or parameter	Baseline PPW model	Optimal PPW model
Production	Printed wiring board	0.93 kilograms	0.90 kilograms
Use	Number of laundry cycles	220	220
Use	Washing programme	100% standard cotton (40°C)	25% standard cotton + Eco (60°C)
			25% standard cotton + Eco (40°C)
			25% easy care (40°C)
			25% hand wash (30°C)
Use	Electricity use per laundry cycle	1.3 kWh	0.62 kWh (average)
Use	Water use per laundry cycle	73 litres	56.5 litres (average)
Use	Electricity mix	100% average Dutch electricity mix (ecoinvent)	90% average Dutch electricity mix (ecoinvent)
			10% from PV panels
Repair	Distance travelled	100 kilometres in total	25 kilometres in total
Repair	Emission class car	EURO4	EURO5
Repair	Test cycle	1.3 kWh of electricity and 73 litres of water	0.62 kWh of electricity and 56.5 litres of water
Assumptions	Contract duration	4 years	5 years
Assumptions	Lifetime of the washing machine	24 years	30 years

The sensitivity analysis showed the large influence of the printed wiring board on the total environmental impact. Although the PPW model needs to be Wi-Fi enabled to provide bills to customers, an optimal PPW model would keep the printed wiring board as small as possible, thereby limiting the software, electronics and Wi-Fi functions to the essentials. The optimal PPW model thus limits the weight of the printed wiring board to 0.90 kilograms: the same weight as the sales model.

To be able to compare the baseline PPW model and the optimal PPW model, the number of laundry cycles per year is kept constant. For the sake of simplicity, the household in the baseline model used only one washing programme: standard cotton at 40°C, using 1.3 kWh of electricity and 73 litres of water. However, it is reasonable to believe that a household uses several washing programmes for different types of washes. Standard cotton is the most used washing programme, followed by easy care and hand wash; most washes are done at 40°C, followed by 30°C and 60°C, see also section 6.3 and Appendix E. This is reflected in the washing programmes of the optimal PPW model: 50% standard cotton and 50% at 40°C. User type B in chapter 6 showed that pressing the Eco button reducing the water use. In the optimal PPW model the household thus always presses the Eco-button to save water in the standard cotton programme. The average electricity use and water use per laundry cycle of the four washing programmes is in this way reduced to respectively 0.62 kWh and 56.5 litres. While chapter 6 and chapter 7 revealed that electricity use contributes substantially to the environmental impact, chapter 5's sensitivity analysis additionally revealed that a country's electricity mix is also an influential factor. For the optimal PPW model it was therefore assumed that the household receives 10% of electricity from PV panels on their roof. The ecoinvent process 'electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted' was used for this (Treyer, n.d.b).

The contribution analysis in chapter 5 showed that the repair phase is the second most contributing life cycle phase of the PPW model. In the optimal PPW model, efforts are pointed at reducing the impact of the repair as much as possible. An employee from ATAG in the Netherlands (daughter of Gorenje) confirmed that the 100 kilometres driven by the service engineer in the baseline can be considered a worst case scenario. They aim for a decentral approach in the repair service, where several service engineers are spread across the country. The service engineer would then drive 75-100 kilometres in a day, visiting 8-10 customers per day. This results in utmost 25 kilometres per customer (J. van Os, personal communication, 17 December 2020). The impact of the repair phase could be further reduced by an economic car, here assumed to have a EURO5 emission standard instead of EURO4. In the future the service engineer could possibly even drive an electric car. Lastly, the electricity and water use of the test cycle run by the service engineer is reduced in line with the electricity and water use of the use phase.

Chapter 5 showed that extending the lifetime of the PPW model reduces the environmental impact, therefore the optimal PPW model has a contract for 5 years per customer; in this way extending the lifetime to 30 years (6 customers * 5 years per customer).

8.4. Results

8.4.1. Without price incentive

Figure 23 shows the results of the analysis, in which the optimal PPW model (with its characteristics as summarised in table 29) is compared to the baseline PPW model. The combination of all influential factors in the model can substantially reduce the environmental impact across all impact categories. The impact category resources: fossils can be reduced with 45% and the impact category climate change with 44.5%. All other impact categories show reductions between 24% and 41%. This proofs that further optimalisation of the PPW model in the electronics component, in the use and repair phase and for the contract duration results in even more reductions in environmental impact.

Figure 24 shows the life cycle contribution analysis of the optimal PPW model, which can be compared to figure 7, the life cycle contribution analysis of the baseline PPW model. No major shifts appear here. The largest difference can be observed in the repair phase, which relative contribution to the total environmental impact is reduced for all impact categories. This results in a slightly larger relative contribution for the refurbishment phase.

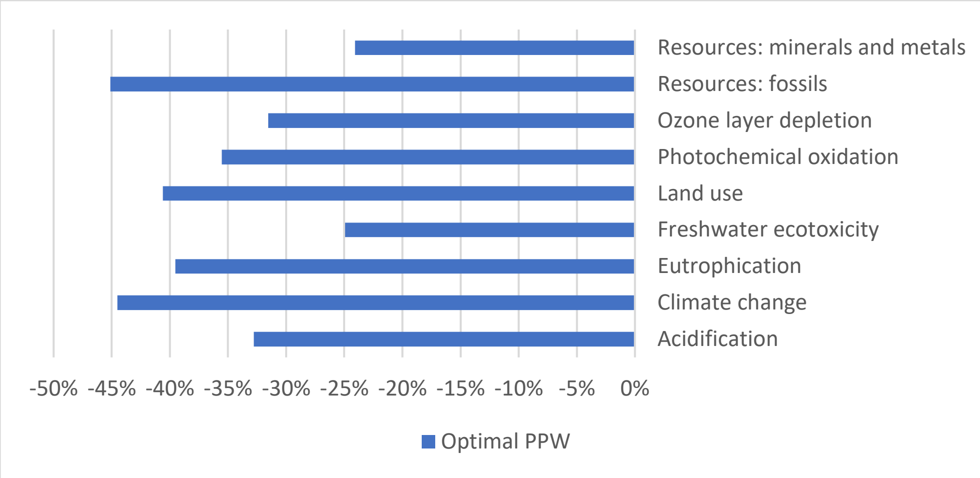

Figure 23: Change in environmental impact per impact category for the optimal PPW model. Compared to the chapter 5 baseline PPW model.

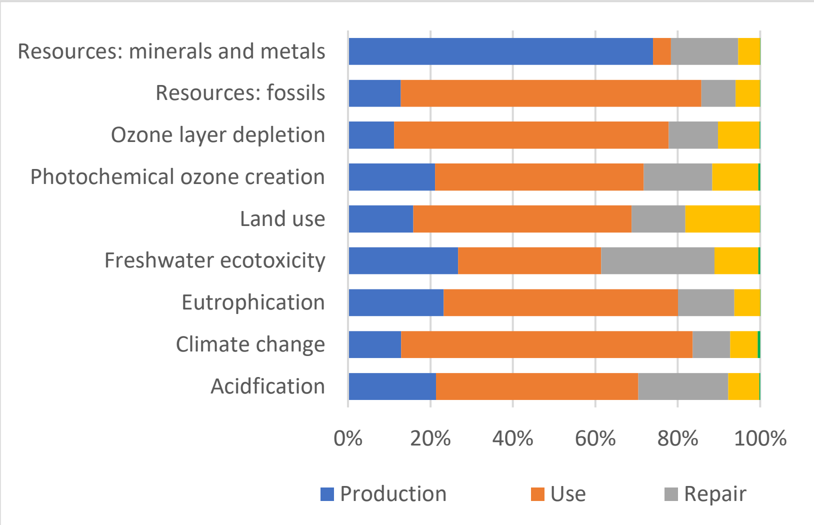

Figure 24: Life cycle stage contribution analysis of the optimal PPW model

8.4.2. After introduction price incentive

The optimal PPW model did not include the price incentive as discussed in chapter 5 yet, although it could achieve a lower number of laundry cycles and lower average washing temperature. The same analysis as performed in chapter 7 is applied to the optimal PPW model. That results in the number of laundry cycles, average washing temperature and related electricity and water use as presented in table 30.

The analysis yields results that provide the same rounded reductions in percentages for the worst and best case scenario – the differences are about 0.03% or less. The worst and best case scenario are thus the same and shown as one in the figure. Figure 25 demonstrates that adding a price incentive - consisting out of a minimum amount per wash and a proportionally higher amount for laundry cycles at warmer temperatures – can further reduce the environmental impact of the optimal PPW model. All impact categories can be reduced with at least 5% if such a price incentive is added to the model. Figure 26 combines figure 23 and figure 25. Figure 26 presents that if the PPW model is optimised in the way suggested in this chapter, reductions of at least 26% are possible, leading up to 47% for climate change and 48% for resources: fossils.

Table 30: Characteristics of the optimal PPW model, after introduction of price incentive (= p.i.), following the data from Bocken et al. (2018) when average number of laundry cycles and average washing temperature are reduced

	Baseline PPW	Optimal PPW	Optimal PPW	
		Without p.i.	With p.i.	
			Best case	Worst case
Number of laundry cycles (per year)	220	220	179.2	179.2
Average temperature (°C)	40	42.5	38.3	40.7
Related electricity use (kWh)	1.3	0.62	0.54	0.58
Related water use (litres)	73	56.5	57.2	57.1

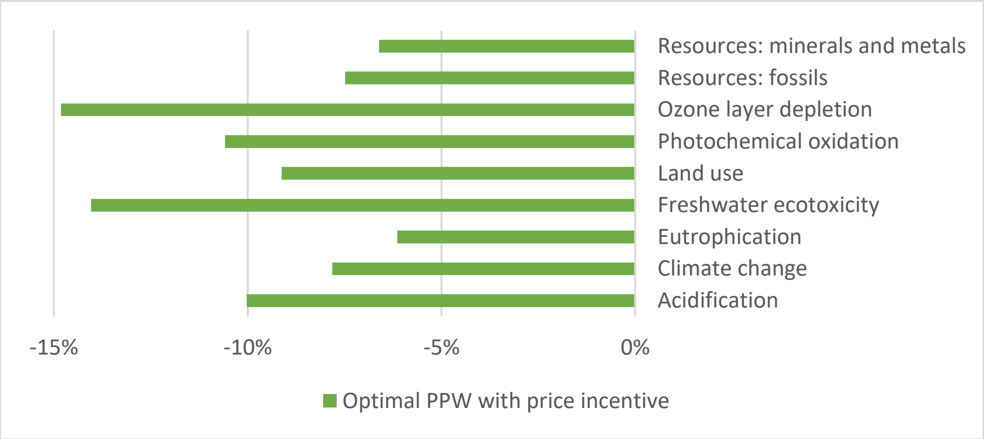

Figure 25: Change in environmental impact per impact category for the optimal PPW after introduction of the price incentive. Compared to the optimal PPW model from section 6.4.1

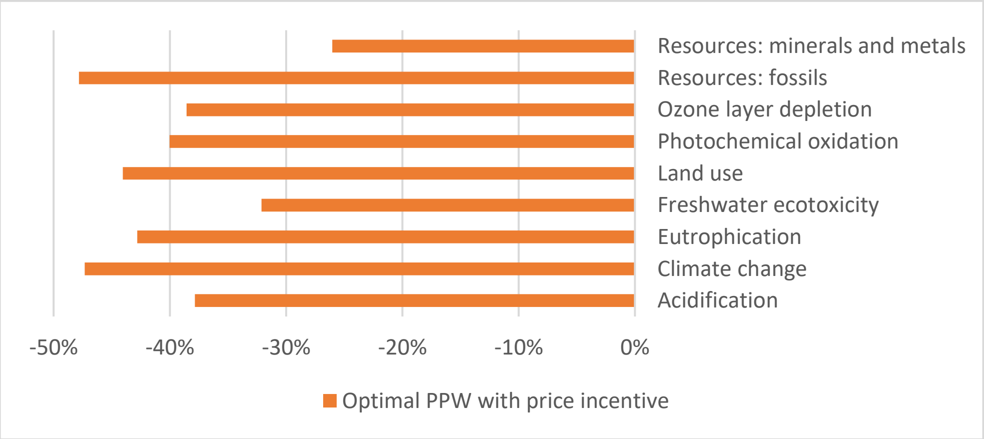

Figure 26: Change in environmental impact per impact category for the optimal PPW after introduction of the price incentive. Compared to the baseline PPW model in chapter 5

8.5. Chapter summary and conclusion

Chapter 8 introduced a list of influential factors that could further reduce the environmental impact of the PPW model in the future. The influential factors were mostly aimed at reducing the impact of the use and repair phase, but the production and lifetime of the washing machine were not left out. Some of the measures for customers that would optimise the PPW model are: differentiating between different washing programmes, pressing the Eco-button and installing PV panels (if possible, of course). For Gorenje, the optimised PPW model focuses on reducing the impact of the repair phase, by not driving further than 25 kilometres per customer in a low-emission car. Moreover, adding a price incentive to the PPW model has proven – like in chapter 7 – to have the potential to reduce environmental impact with at least 5% and up to 15%. On the whole, all measures combined reduce the environmental impact of the PPW model with at least 26% and up to 47% for climate change and up to 48% for resources: fossils, compared to the PPW model in the baseline scenario (chapter 5).

The sub question of this chapter is: *how can the Gorenje pay-per-wash model be further optimised and which (behavioural) changes are needed to achieve this?* The first part of this question is answered by the set of measures presented in table 29, complemented with the price incentive. The second part of the sub question can be answered for two parties: producer and customer. The producer needs to take the effect of electronics and the repair phase into account when switching to a pay-per-use business model. The additional software and services in such a business model contribute to the total environmental impact and these impacts should be kept to a minimum to prevent offsetting the environmental reductions. The extent to which a customer needs to change his/her behaviour depends on his/her behaviour before introduction of a PPW model. Chapter 6 already showed how different behaviour results in varying impact across impact categories. Chapter 8 additionally showed that behavioural changes like 'always pressing the Eco-button when washing with the standard cotton programme' can contribute to lower environmental impacts. Furthermore, the customer's sensitivity to the price incentive determines to a large extent how successful this part of the PPW model is in reducing environmental impact. This touches on the concept of consumer acceptance, which will be discussed in the discussion below.

Chapter 9: Discussion

This chapter discusses the results of chapter 3 up till chapter 8 and brings some of the implications and issues around the results and largely contributing factors to light. Section 9.1 discusses some of the findings combined, to place these in a broader perspective. Section 9.2 discusses the trade-off between lifetime extension and energy efficiency of products. Furthermore, section 9.3 and 9.4 discuss this research in the wider context of consumer acceptance and the issues around the largely contributing factors to the total environmental impact of the washing machine.

9.1. Discussion of the results

Chapter 3 concluded that PPS are not inherently sustainable and that their environmental potential depends on their design and differs per case. This was confirmed by the LCA in chapter 5, which showed that the environmental impact of the sales and PPW model were relatively close to each other. The proximity of the two models in terms of environmental impact at least confirms that the PPW model is not necessarily environmentally benign. Furthermore, an interesting finding comes from sensitivity analysis 9, which showed that when the ReCiPe method is applied, the PPW model has a larger environmental impact on urban land occupation and terrestrial ecotoxicity. All of this confirms that same finding again: the PPW model – and probably PSS in general – does not have a positive environmental impact by definition. However, chapter 8 found that the PPW model has, under changed assumptions, considerable potential to further reduce environmental impacts. Since an optimal sales model is not defined in this research, the optimal PPW model cannot be compared to the traditional sales model under unoptimised circumstances.

Another finding of the literature review in chapter 3 was the extended lifetime of a product as a potential benefit of PPS. This benefit was later found to be one of the main and most influential assumptions in the LCA in chapter 5 and was also found to be a contributing factor to reducing the environmental impact of the washing machine. Gorenje extends the lifetime of the washing machine in practice by better maintenance (repair and refurbishing), 'designing-to-last' and extending the use phase of the washing machine by contract durations and serving multiple customers with one washing machine. The lifetime of the sales model was, based on literature, set at 12 years. Tecchio et al. (2019) found that the lifetime of a washing machine is only extended to 13.2 years if repaired by a service engineer. However, exceptions to this lifetime are not unthinkable. Since the same type of washing machine (ASKO W4086C) is assumed for both the sales and PPW model, the sales model could in theory also last 24 years. Especially if a customer carefully uses the washing machine and maintains it well, the lifetime might be extended to more than 12-13 years. Furthermore, washing machines are often given a second life at the second hand market. That was completely left out of this thesis, but such effects might also reduce the environmental impact of the sales model.

Chapter 7 and chapter 8 exposed the positive environmental effects of a price incentive as introduced in Bocken et al. (2018). However, this study has also some limitations. Firstly, the *n* in this study is rather small: 56 households for the two-month sample group and 21 households for the five-month sample group. Secondly, the measurements are performed over a relatively short period of time. The effect of the introduction of the PPW model is strongest in month 2 (when the PPW model is first introduced). Not everyone adopts the new habit of washing less often and at lower temperatures and for some the washing temperature even increases again after three months. It is thus not so evident whether people would still wash less often and at lower temperatures after one or even five years' time.

9.2. Trade-off: lifetime extension versus use phase

As already mentioned in chapter 3, Ardente and Mathieux (2014) focus in their study on a discussion that is held in literature on the trade-off between extending a product's lifetime and the improved energy-efficiency of most recent products. Ardente and Mathieux (2014) identify washing machines as consumer durables with a relatively large technology cycle and therefore they are suitable for 'design for durability' or lifetime extension. However, since most of the environmental impacts occur in the use phase, some authors also argue that energy efficiency improvements should be prioritised over lifetime extension.

The discussion on this trade-off can also be applied to this research. On the one hand, it is realistic to assume that the PPW model extends the lifetime of the washing machine to about 24 years. As such, it can reduce environmental impacts compared to the sales model. However, if the PPW model does not achieve at lifetime extensions, it probably will not reduce environmental impacts compared to a sales model, as shown in the combined sensitivity analysis. On the other hand, this research confirmed the large contribution of the use phase to the total environmental impact and also identified that various types of users cause a range of environmental impacts for different impact categories. This moves beyond the point of just prioritising energy efficiency improvements, but adds the notion that consumer behaviour in the use phase largely influences the environmental impact of a washing machine.

The question then remains which one of the two should be prioritised. It could be argued that there lays a task here for both producers *and* consumers. Producers have the capability to design for durability and when they offer a PPW model, they are incentivised to take the full life cycle of washing machines into account. Repairs and refurbishment come at the cost of producers and they will be more motivated to repair the washing machine than consumers, who are discouraged by the costs of spare parts and labour (Tecchio et al., 2019). For consumers, there lays a task in adopting environmentally sustainable washing behaviour. This research suggests that although washing machines could either be energy efficient or not: laundry behaviour of consumers affects the environmental impact of a washing machine notably. This points back to Shahmohammadi et al. (2018), as also discussed in chapter 3, who state that the range of consumer behaviour can heavily influence the environmental impact of washing, but that this range is often neglected in LCAs. The range of consumer behaviour is also neglected in the discussion on the trade-off lifetime extension versus energy efficiency, while the range of consumer behaviour might contribute more to the environmental impact in the use phase than the energy efficiency of the washing machine.

9.3. Consumer acceptance

The large contribution and therewith the importance of the use phase is demonstrated multiple times in this report. That means that while producers could try to lower their environmental impact in the production process, still a large share of the environmental impact will come from consumers and their behaviour in the use phase. The way in which consumers perceive new sustainable business models, such as PSS and pay-per-use models more specifically, can make or break their success. Consumer acceptance of the PPW model was left out of this research. However, to get an idea if consumers would accept such a model or not, several factors are relevant. Elzinga et al. (2020) study consumer acceptance of take back management, product lease and pay-per-use and find that consumers prefer take back management over lease and pay-per-use. The studied variables dealt with ownership, responsibility of the consumer and payment structure. It was found that the altered payment scheme in lease and pay-per-use leads to lower acceptance. Elzinga et al. (2020) advise companies to accurately consider consumers' habits, since this may lead to a more gradual adoption of new business models. Moreover, Elzinga et al. (2020) found that the absence of ownership does not negatively influence consumers' acceptance of pay-per-use models, which in turn advances consumer acceptance of the introduction of pay-per-use models.

Linked to consumer acceptance is consumer experience: how do consumer value their washing machine and what is the intangible value of a washing machine? A product's intangible value can be for example experience, brand value, sense of control or access (Tukker, 2015). An often mentioned illustration here is the functionality of cardboard packaging and glass packaging. Both would have equal functionality in an LCA. However, wine drinkers experience drinking wine from a glass bottle differently than drinking the same wine from a cardboard box. Hence, the glass bottle and cardboard box have different intangible functionalities and value – although they provide the same function (Tukker, 2015). This could also be true for washing machines offered as PSS. A washing machine sold to the user; a PPW model at home; a shared washing machine in an apartment flat; and outsourcing your laundry to a laundromat all have different intangible values (Komoto et al., 2005 as cited in: Tukker, 2015). Customers might care about easy access to the washing machine at home (sales and PPW) or dislike the planning that comes along with a shared washing machine or laundromat. The intangible value of 'having ownership of the washing machine' is however found to be less important for consumers in Elzinga et al. (2020) as stated above. Kjaer et al. (2017, 2018) also discussed the intangible value of products in their guidelines on performing an LCA on a PSS. They state that a product can fulfil other non-functional utilities, subjective value and consumption factors (such as money, time, space, skills, information, access, convenience) besides the actual function. This is more elaborately discussed in Appendix B, section B.3.3. All in all, this shows that there could be other factors than costs and environmental effects to consider when producers want to 'convince' consumers to choose for a PPW model.

9.4. Largely contributing factors to the environmental impact of the washing machine

The results of the LCA presented that, among others, a country's electricity mix and the electronics component of the washing machine contribute largely to the total environmental impact of the washing machine.

The contribution of the electricity mix shows the urgency for countries to move away from fossil fuels for electricity supply. Many appliances, not just washing machines, consume relatively large quantities of electricity and as long as countries' electricity mixes are as carbon intensive as they are now in the Netherlands, these appliances will have more environmental impact than necessary. Offering a washing machine in a sustainable business model, like a PPW model, will not change that. The Dutch goal of having 27% clean energy supply by 2030 is less ambitious than the goal of countries around us (Rijksoverheid, n.d.). Accelerating the share of renewable energy in the Dutch electricity mix will also reduce the environmental impact of electricity consuming household appliances, like washing machines.

Secondly, there is the impact from the electronics component on the environment, especially for the impact category resources: minerals and metals. Increasing the weight of the printed wiring board from 0.9 kilograms to 0.93 kilograms seems like a minor adjustment, however, the results of the LCA have demonstrated how much this component contributes to the environmental impact. Having a Wi-Fi-enabled washing machine fits our contemporary time, in which the Internet of Things has become common practice and where almost all appliances in and around our homes can be run by our smartphone. But this increased connectivity has a flipside, since it severely increases the impact on the environment. For instance, datacentres in the Netherlands now consume more electricity in a year than the Dutch Railways need for operating all their trains (Rengers & Houtekamer, 2020). The concern for increased environmental impact from electronics, internet services and data storage, while that impact is insufficiently noticed in literature, is also shared in Martin et al.'s (2019) discussion. They determine that although it is a minor impact in the study he performs, the potential impacts of (internet) services and electronics should be more extensively reviewed.

Chapter 10: Conclusion and recommendations

10.1. Conclusion

The research question of this study is: *under which conditions can a pay-per-wash model reduce environmental impacts compared to a traditional sales model?*

It was found that a pay-per-use model (as sub category of product-service systems) does not necessarily always lower environmental impacts compared to a traditionally sold product. Product-service systems (PSS) have the potential to reduce environmental impacts through dematerialisation, extending the lifetime, optimising the end-of-life and incentivising producers towards environmental sustainability; however, that does not mean that PSS are inherently more sustainable than providing the sole product. For a PSS to be sustainable and to guarantee resource efficiency, they should be purposely designed with this goal in mind. Designing a pay-per-use model with circularity and improving the environmental performance in mind, enhances its chances to reduce environmental impacts.

Previous case studies and Life Cycle Assessments (LCAs) showed that extending the lifetime of the washing machine can lead to some positive environmental impacts. Moreover, since the use phase is largely contributing to the total environmental impact and consumer behaviour influences this impact, a PSS could reduce environmental impacts if it achieves to reduce impacts in the use phase or changes a customer's behaviour towards more environmentally sustainable behaviour.

In this research's case study, the LCA results showed that the environmental impact of the sales and PPW model are relatively close to each other. The proximity of the two models in terms of environmental impact presents that the PPW model does not necessarily reduce environmental impact and that some conditions need to be met. Accordingly, it was found that this specific PPW model has lower environmental impacts than the sales model if the following conditions are met.

Firstly, the lifetime of the PPW model is extended. Gorenje does this by better maintenance (repair and refurbishing), 'designing-to-last' and extending the use phase of the washing machine by contract duration and serving multiple customers with one washing machine. The repair and refurbishment that are added to the PPW model have its impact on the environment, but not to an extent in which it diminishes the positive environmental impacts from the extended lifetime. The combined sensitivity analysis in this research suggested that if this condition is not met, the PPW model will not reduce environmental impact compared to the sales model.

Secondly, the PPW model can incentivise customers to wash less often and at lower temperatures. In this study, that was referred to as the 'price incentive': (i.e. households pay per wash and pay proportionally higher amounts for washes at higher temperatures). Although the long-term evidence for such a price incentive is limited, the PPW model could reduce environmental impacts compared to a traditional sales model if the pricing scheme of the PPW model pushes customers towards more environmentally friendly laundry behaviour. Moreover, this could be done by advising or incentivising customers to press the eco-button when choosing the 'standard cotton'-washing programme, to minimise laundry cycles at 60°C when that temperature is not required and to choose the washing programme that fits the type of laundry. For the latter two, Gorenje can play an active role in advising customers what types of washes require higher temperatures and which washing programmes fit which types of washes. Although such features are not completely unattainable for a sales model, it is reasonable to believe that the payment structure and incentives in a PPW model make it easier to achieve environmentally sustainable laundry behaviour.

All in all, the physical difference between the sales model and the PPW model is not so considerable and it does not provide the condition to reduce environmental impacts. It is the lifetime extension of the washing machine – with the incentive for producers to design with circularity in mind and take responsibility for maintenance and repair – together with sustainable consumer behaviour, which can be more easily affected in a PPW model than in a sales model, that provide the conditions to reduce the environmental impact of a PPW washing machine.

It should be noted that these conditions do not provide a generalisable answer to the question under which conditions a pay-per-wash system (or more broadly: any pay-per-use or product-service system) reduces environmental impacts compared to a traditional sales system. This research has shown that the factors above reduce the environmental impact of this specific PPW model, under the assumptions as made in this research.

10.2. Limitations

Limitations of this study are the following.

This study is an attributional LCA, which means that current demand and average processes and behaviour are modelled (as opposed to marginal processes and behaviour). LCA is furthermore a static way of modelling, as opposed to dynamic. This results in the fact that this study could not model the actual changes that are caused by the system over time. Consequently, the production, repair and refurbishment process are assumed as average processes at a static moment in time. In reality, interactions between these processes might cause alterations in the quantities of the processes. For example, Gorenje could replace a washing machine's component in the refurbishment process and afterwards modernise this used component to be ready for reuse. As such, the modernised component can function as a spare part in the repair process, where the service engineer replaces a broken component with the modernised component. All of this would decrease primary material demand, but such interactions can now not be modelled.

Other limitations relate to the content of this study. Firstly, the price incentive as discussed in chapters 7 and 8 (i.e. households will do the laundry less often and at lower temperatures if they pay per wash and pay proportionally higher amounts for washes at higher temperatures) is based on only one study (Bocken et al., 2018). This study also has its limitations, namely a small sample size and measurements over a relatively short time span (these limitations are more elaborately discussed in section 9.1 above). The fact that the analysis in this research is based on one study only that was performed over a five-month time span, weakens the reliability of the findings. More research can be done to this end, as more elaborately discussed below (section 10.3.2).

Secondly, the user types as defined in chapter 6 are not based on real data and so, many assumptions needed to be made here. The limited scientific character of these user types decreases their accuracy. Nevertheless, formulating the user types with the assumptions as was done, still fitted the aim of the chapter. It showed how differently various households can behave and their consequent influences on the environmental impact. If Gorenje has introduced their PPW model, more research can be done on this (see also section 10.3.2).

Thirdly, data on the production process was based on a fast-track LCA done in 2014 since this was the only data made available for this LCA. This data is an older washing machine model and not the real ASKO W4086C type. Dismantling the ASKO W4086C, weighing all the components and having an expert judge the production technology per component (as was done in the fast-track LCA, see appendix C, section C.1.1) would result in more accurate production data. However, data from the 2014 washing machine model comes close to the ASKO W4086C model and since the only physical difference between the sales and PPW model is the weight of the electronics component, the slight outdatedness of the data probably does not impact the results much.

10.3. Recommendations

10.3.1. Recommendations for Gorenje

Based on the findings of this research, several recommendations to Gorenje can be formulated. Firstly, the price incentive as introduced by HOMIE is a strongly advised, since it can substantially contribute to lowering the environmental impact of the PPW washing machine. Compared to a PPW model without a price incentive, incorporating a price incentive in the payment scheme for consumers reduces environmental impacts for households like user type A and B by 5% to 10%, for households like user type C and D by 10% to 25% and for households like the baseline scenario up to 35%. Although the findings have its limitations as formulated above in section 10.2, the results are worth exploring what the Gorenje price incentive should look like.

That leads to a second broader recommendation: investigate the habits and wishes of your customers and know what your customers want. This recommendation can be illustrated in the following way.

To achieve the largest reduction in environmental impact, it is advised to not focus on the 'eco conscious' kind of customers. The findings have shown that largest environmental impact reductions can be achieved at those who do the laundry more often and at higher temperatures. Consequently, such customers might care a lot less about the environmental performance of a pay-per-wash washing machine and might not be attracted to marketing focused on the positive environmental effects of a PPW model. Therefore, it is advised to reach these customer groups by emphasising other benefits that the PPW model could have for them, such as economic or feasibility aspects (see also the discussion on intangible value in section 9.3). Knowing what your customers want is thus key in tailoring the marketing around those wishes combined with the benefits of the PPW model.

A last recommendation concerns the production and repair process. If Gorenje wants to further reduce the environmental impact of the PPW washing machine, the focus should lay on the repair process and the production process, more specifically the electronics component. The results showed that the repair process follows up the use phase in contribution to the environmental impact of the PPW model. To minimise the total environmental impact of the PPW model, it is advised to keep the environmental impact of the repair process as small as possible by optimising the travelling of the service engineer. This can be achieved by a limited number of kilometres driven and a fuel efficient, or even an electric car. The impact of the production process is best minimised by acknowledging the impact of the electronics component. The additional software and Wi-Fi in the PPW model contribute to the total environmental impact and these impacts should be kept to a minimum to prevent offsetting the environmental reductions.

10.3.2. Recommendations for future research

Future research could include the following.

Foremost, more research needs to be done on the behavioural variance of customers, their behaviour after introduction of a PPW model and rebound effects. Behavioural surveys on laundry exist, but they provide only averages. Research on which variables lead to typical behaviour is missing (think of for example: age influencing the average washing temperature, household size influencing the number of laundry cycles, eco-mindedness influencing the chosen washing programme). Research on the behavioural variance of customers improves the definition of user types as was done in chapter 6. Little is also known on how customers behave after introduction of pay-per-use business models, let alone pay-per-wash specifically. Bocken et al.'s (2018) study covered a too short time span (five months) to find out if customers really changed their behaviour over a longer period of time. If Gorenje introduces their PPW model, data on customer's behaviour changes can be used to study that effect. Lastly, the rebound effects that could occur after introduction of a PPW model should be investigated and, possibly, quantified. By taking the rebound effects into account it will appear if the achieved environmental reductions are not offset by such effects.

Besides, more work can be done on allowing LCAs on circular economy products in the Activity Browser. The Activity Browser does not (yet) allow for multifunctionality and circular economy loops within a product's life cycle. In this research, the repair and refurbishment process in the PPW model would rather be modelled as loops. Those processes are now added as a service to the use phase. As a result, the life cycle of the PPW model is still modelled in a fairly linear way. If more environmental impact assessments need to be performed comparing a 'traditional' product and a circular economy product in the future, the Activity Browser might not yet be suited for those tasks.

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Appendix A – List of key papers

Appendix A.1 – Chapter 3

A.1.1. First search

Table A.1: list of key papers, selected after the first search

Author and year	Title and journal
Amasawa et al., 2020	Environmental potential of reusing, renting, and sharing consumer products: Systematic analysis approach. *Journal of Cleaner Production*, *242*, 118487.
Annarelli et al., 2017	Predicting the value of Product Service-Systems for potential future implementers: results from multiple industrial case studies. *Procedia CIRP*, *64*(2017), 295-300.
Bech et al., 2019	Evaluating the environmental performance of a product/service-system business model for Merino Wool Next-to-Skin Garments: The case of Armadillo Merino®. *Sustainability*, *11*(20), 5854.
Bertoni, 2019	Multi-criteria decision making for sustainability and value assessment in early PSS design. *Sustainability*, *11*(7), 1952.
Chen & Huang, 2019	Application review of LCA (Life Cycle Assessment) in circular economy: From the perspective of PSS (Product Service System). *Procedia CIRP,* 83, 210-217.
Chen et al., 2019	A rough-fuzzy DEMATEL-ANP method for evaluating sustainable value requirement of product service system. *Journal of Cleaner Production*, *228*, 485-508.
Copani & Behnam, 2018	Remanufacturing with upgrade PSS for new sustainable business models. *CIRP Journal of Manufacturing Science and Technology, 29*, 245-256.
Ding et al., 2017	Environmental and economic sustainability-aware resource service scheduling for industrial product service systems. *Journal of Intelligent Manufacturing*, *28*(6), 1303-1316.
Fargnoli et al., 2019	PSS modularisation: A customer-driven integrated approach. *International Journal of Production Research*, *57*(13), 4061-4077.
Junnila et al., 2018	Influence of reduced ownership on the environmental benefits of the circular economy. *Sustainability*, *10*(11), 4077.
Kühl et al., 2018	Implementation of Circular Economy principles in PSS operations. *Procedia CIRP*, *73*(1), 124-129.
Moon et al., 2019	Laundry Habits in Bangkok: Use Patterns of Products and Services. *Sustainability*, *11*(16), 4486.
Pacheco et al., 2016	Systematic eco-innovation in PSS: state of the art and directions. *Procedia CIRP, 47*, 168-173.
Peeters et al., 2017	Economic and environmental evaluation of design for active disassembly. *Journal of Cleaner Production*, *140*, 1182-1193.

Pialot et al., 2017	"Upgradable PSS": Clarifying a new concept of sustainable consumption/production based on upgradability. *Journal of Cleaner Production*, *141*, 538-550.
Plepys et al., 2015	European policy approaches to promote servicizing. *Journal of Cleaner Production*, *97*, 117-123.
Riesener et al., 2019	Implications of Service-related Business Models on Product Development Processes. *Procedia CIRP*, *80*, 756-761.
Scheepens et al., 2016	Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257-268.
Tu et al., 2013	Construction of customization development procedures in product service systems. *Journal of Industrial and Production Engineering*, *30*(5), 303-326.
Tukker, 2015	Product services for a resource-efficient and circular economy–a review. *Journal of Cleaner Production*, *97*, 76-91.
Tukker, 2004	Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment*, *13*(4), 246-260
Wasserbaur et al., 2020	What if everyone becomes a sharer? A quantification of the environmental impact of access-based consumption for household laundry activities. *Resources, Conservation and Recycling*, *158*, 104780.
Zheng et al., 2019	Is bicycle sharing an environmental practice? Evidence from a life cycle assessment based on behavioral surveys. *Sustainability*, *11*(6), 1550.

A.1.2. Backward snowballing

Table A.2: list of papers, selected through backward snowballing after the first search

Author and year	Title and journal
Beuren et al., 2013	Product-service systems: a literature review on integrated products and services. *Journal of Cleaner Production*, *47*, 222-231.
Blomsma et al, 2018	Exploring circular strategy combinations-towards understanding the role of PSS. *Procedia CIRP*, *69*, 752-757.
Doualle et al., 2015	Investigating sustainability assessment methods of product-service systems. *Procedia CIRP*, *30*, 161-166.
Grazia Gnoni et al., 2017	Supporting circular economy through use-based business models: the washing machines case. *Procedia CIRP*, *64*(1), 49-54.
Khan et al., 2018	Review on upgradability–A product lifetime extension strategy in the context of product service systems. *Journal of Cleaner Production*, *204*, 1154-1168.
Kjaer et al., 2019	Product/service-systems for a circular economy: the route to decoupling economic growth from resource consumption?. *Journal of Industrial Ecology*, *23*(1), 22-35.
Mont, 2002	Clarifying the concept of product–service system. *Journal of Cleaner Production*, *10*(3), 237-245.

Reim et al., 2017	Implementing sustainable product–service systems utilizing business model activities. *Procedia CIRP, 64*, 61–66.
Roy, 2000	Sustainable product-service systems. *Futures*, *32*(3-4), 289-299.
Tukker & Tischner, 2006	Product-services as a research field: past, present and future. Reflections from a decade of research. *Journal of Cleaner Production*, *14*(17), 1552-1556.

A.1.3. Second search

Table A.3: list of key papers, selected after the second search in December 2020

Author and year	Title and journal
Baldassare et al., 2020	Implementing sustainable design theory in business practice: A call to action. *Journal of Cleaner Production*, *273,* 123113.
Blüher et al., 2020	Systematic Literature Review—Effects of PSS on Sustainability Based on Use Case Assessments. *Sustainability*, *12*(17), 6989.
Da Costa Fernandes et al., 2020	Towards product-service system oriented to circular economy: A systematic review of value proposition design approaches. *Journal of Cleaner Production*, *257*, 120507.
Hüer et al., 2018	Impacts of product-service systems on sustainability–a structured literature review. *Procedia CIRP*, *73*, 228-234.
Lugnet et al., 2020	Design of Product–Service Systems: Toward an Updated Discourse. *Systems*, *8*(4), 45.
Muñoz Lopez et al., 2020	Sustainability assessment of product–service systems using flows between systems approach. *Sustainability*, *12*(8), 3415.
Neramballi et al., 2020	A design navigator to guide the transition towards environmentally benign product/service systems based on LCA results. *Journal of Cleaner Production*, *277*, 124074.
Peruzzini et al., 2019	Emergence of Product-Service Systems. In: *Systems Engineering in Research and Industrial Practice,* 209-232, Springer, Cham.
Pigosso & McAloone, 2016	Maturity-based approach for the development of environmentally sustainable product/service-systems. *CIRP Journal of Manufacturing Science and Technology*, *15*, 33-41.

Appendix A.2 – Chapter 4

A.2.1. First search

Table A.4: list of key papers, selected by the search term as presented in the main text

Author and year	Title and journal
Bech et al., 2019	Evaluating the environmental performance of a product/service-system business model for Merino Wool Next-to-Skin Garments: The case of Armadillo Merino®. *Sustainability*, *11*(20), 5854.
Bracquené et al., 2020	Measuring the performance of more circular complex product supply chains. *Resources, Conservation and Recycling*, *154*, 104608.

Chen & Huang, 2019	Application review of LCA (Life Cycle Assessment) in circular economy: From the perspective of PSS (Product Service System). *Procedia CIRP,* 83, 210-217.
Dal Lago et al., 2017	Reinterpreting the LCA standard procedure for PSS. *Procedia CIRP*, *64*, 73-78.
Glatt et al., 2019	Technical Product-Service Systems: Analysis and reduction of the Cumulative Energy Demand. *Journal of Cleaner Production*, *206*, 727-740.
Kjaer et al., 2016	Challenges when evaluating product/service-systems through life cycle assessment. *Journal of Cleaner Production*, *120*, 95-104.
Kjaer et al., 2018	Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment. *Journal of Cleaner Production*, *190*, 666-678.
Muñoz Lopez et al., 2020	Sustainability assessment of product–service systems using flows between systems approach. *Sustainability*, *12*(8), 3415.
Peruzzini et al., 2013	A sustainability lifecycle assessment of products and services for the extended enterprise evolution. In: *IFIP International Conference on Product Lifecycle Management,* 100-109, Springer, Berlin, Heidelberg.
Shahmohammadi et al., 2018	Quantifying drivers of variability in life cycle greenhouse gas emissions of consumer products—a case study on laundry washing in Europe. *The International Journal of Life Cycle Assessment*, *23*(10), 1940-1949.
Sousa-Zomer and Miguel, 2018	The main challenges for social life cycle assessment (SLCA) to support the social impacts analysis of product-service systems. *The International Journal of Life Cycle Assessment*, *23*(3), 607-616.
Zhang et al., 2011	Environmental impact and cost assessment of product service systems using IDEF0 modeling. *Proceedings of NAMRI/SME*, *39*.

A.2.2. Backward snowballing

Table A.5: list of papers, selected through backward snowballing

Author and year	Title and journal
Amasawa et al., 2018	Designing interventions for behavioral shifts toward product sharing: The case of laundry activities in Japan. *Sustainability*, *10*(8), 2687.
Amasawa et al., 2020	Environmental potential of reusing, renting, and sharing consumer products: Systematic analysis approach. *Journal of Cleaner Production*, *242*, 118487.
Doualle et al., 2015	Investigating sustainability assessment methods of product-service systems. *Procedia CIRP*, *30*, 161-166.
Scheepens et al., 2016	Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257-268.

Appendix B: LCA setup as followed by guidelines of Kjaer et al. (2017)

This appendix follows the guidelines as formulated by Kjaer et al. (2017) and Kjaer et al. (2018). These guidelines are developed to overcome certain challenges that could arise when modelling PSS. The aim of this appendix is to gain a better understanding of the PSS and reference system under study, to prevent common mistakes that could be made when evaluating PSS through LCA. Some parts of the guidelines are already discussed in the main text, since they resemble the ISO structure; this is indicated by 'as defined in the main text'. Afterwards, the additional steps as proposed by Kjaer et al. are discussed, followed by how these are dealt with in this study.

B.1. Goal definition

B.1.1. Study purpose

Intended audience and goal of the study as defined in the main text.

Additional - This study is done pre-implementation, which means more assumptions need to be made than when the study would have been done post-implementation. Actual data, especially on the use, repair and refurbishment phase are not yet available. As suggested by Kjaer et al. (2017), the study will be more scenario oriented (chapter 6). Because the results are more uncertain (than in a post-implementation study), the focus should not be on the quantified results themselves, but on the learnings throughout the process.

B.1.2. Study complexity

Additional - The study complexity is dependent on the number of application scenarios relevant to include and the number of assumptions to be made (Kjaer et al., 2017). More scenarios and more assumptions result in a more complex study. The number of scenarios is dependent on the reference system and will be relatively high in this study: both the reference system and PSS include several potential scenarios. The number of assumptions is also relatively high: data availability is not really an issue, but uncertainty of the data is high.

> "*Is the PSS only to be operated by a single customer? Then the reference system equals that customer's behaviour, without the PSS, and this is the only application scenario to consider. A single customer perspective can be useful as a pilot study, or as "proof-of-concept". However, if the purpose of the study is to provide knowledge on the more general adoption of the PSS (e.g. all household or whole industry), more application scenarios need to be considered, taking into account the different customers' behaviours. This will increase the study complexity, since more data need to be gathered."* (Kjaer et al., 2017, p. 16).

The above applies to this study, because there are multiple customers (i.e. a household) and also multiple *types* of customers (i.e. old, young, (in)efficient, many/few laundry cycles). This increases the study complexity.

B.1.3. Time and resource

Additional – The available time for the study is five months (September 2020 until January 2021) and no other resources are available. The study is a full LCA (as opposed to a screening LCA).

B.2. PSS and reference system exploration

B.2.1. Scope and reference system

Additional – According to Kjaer et al. (2017), an LCA of a PSS can have three different study scopes, which determine the reference system to study. *PSS consequences* is focused on examining the changes that occur in the reference system as a result of the PSS introduction. *PSS comparison* compares the PSS with a predefined alternative. *PSS optimisation* aims to explore different design options with the PSS itself. This study is a *PSS comparison* and therefore the reference system is a predefined alternative, in this case a traditionally sold Gorenje washing machine.

B.2.2. PSS support and substitutions

Additional - Kjaer et al. (2017) distinguish between three types of PSS support that define what the PSS substitutes. In *activity support* the PSS replaces an activity for the customer. In *product support*, the product is complemented by life cycle service as offered as a service (e.g. lease or pay-per-use). In *platform support*, products and services are offered on a platform.

The PSS of this study is a *product support*. The reference system is the product without the PSS support and a system in which an individual owns the product. Although the PSS substitutes a whole life cycle of a product, it is better to expand the scope including multiple product systems. The reason for this is that the product is taken back at the end-of-life. Because the provider stays the owner of this product in this case, there is a strong incentive to reuse and recycle the product resulting in an extra life cycle for the same product. As a result, all those life cycles need to be included in the LCA.

B.2.3. PSS potential

Additional - Kjaer et al. (2017) advice to qualitatively assess the potential of the PSS beforehand. PSSs do not necessarily bring environmental impact reductions and therefore it is wise to describe the impact reduction potential of the PSS.

The impact reduction potential of this PSS has several elements. First, the washing machine is repaired at the consumer when minor components break down. This prevents bigger failures at a later stage and can lead to a longer lifetime of the product, due to better maintenance. Second, the take-back scheme and refurbishing prolongs the lifetime of the product. Washing machines are effectively recycled by the producer, which can close the material loop. Because the washing machine is refurbished, it can extend into another life cycle at a new customer, whereas otherwise (parts of) the washing machine would have been landfilled. Moreover, the pay-per-wash model incentivises the consumer (economically) to do the laundry less often, which could lead to a less-use situation. This saves energy and water. Lastly, the producer collects information on energy and detergent use by the customer through a build-in Wi-Fi connection. The information can be used to advice the customer on optimised use of the washing machine, while saving energy, water and detergent.

B.2.4. Definition: systems to be analysed

Additional – This step is a final evaluation of the systems to be analysed, based on the answers to the previous sub-steps. This step also includes a first exploration of which scenarios to include, if applicable.

The reference system is a Gorenje washing machine, sold to a household in the Netherlands. An household is assumed to have 220 laundry cycles a year in the baseline scenario.

The PPW system uses the same washing machine as in the reference system, only a piece of Wi-Fi is added. A Gold subscription is used in the baseline scenario, with silver and bronze as optional scenarios. This household is also assumed to have 220 laundry cycles a year in the baseline scenario.

Other scenarios that could be included are a range of household and user types, such as the amount of laundry cycles per year, the temperature of the laundry cycle and the amount of water, detergent and electricity that is consumed. Other scenarios could be related to repaired and refurbished components and its location, electricity mixed and recycling scenarios at the end-of-life.

B.3. Comparability assessment

B.3.1. System functionality and functional unit

The functional unit as defined in the main text is: 1 year of washing a household's laundry.

Additional – Based on the function that the system fulfils, a functional unit is defined. Answering questions like, 'how much?', 'for how long?' and possibly 'where?'. Kjaer et al. (2017) point to three aspects that should be kept in mind while formulating the functional unit. First, the functional unit should be broad enough to capture the functionality of the system and also the sub-systems that it replaces. Also, one should not lock a parameter into the functional unit that could change as a result of the PSS in place. Lastly, the functional unit should be constant between the different alternatives, but the reference flows (how the functional unit is achieved) could vary between the different alternatives.

B.3.2. System subdivision – 'how'

Additional – In this step, the systems are subdivided in processes, to make sure that both systems compare the same processes. Kjaer et al. (2017) give the example of a PSS laundry service that would not give wet clothes wet back to the customer; therefore the drying process needs to be included in both the PSS and the reference system. When carefully subdividing the systems into processes, one can prevent to neglect important processes and thus impacts. Kjaer et al. (2017) distinguish between *avoided impacts* and *induced impacts*. Avoided impacts are processes that are eliminated or altered by the PSS and induced impacts are processes that are added to the system to make the PSS function.

In this research, the drying process is excluded from both systems. The functional unit focusses on the laundry cycles that provide *clean* clothes, not *dry* clothes per se.

Induced impacts of this PSS are the Wi-Fi/software system that is required to run the pay-per-wash model. This system calculates the bill for the customer and also collects information to advice the customer on energy, water and detergent saving.

Avoided impacts can be observed in the end-of-life stage. In the traditional sales system, a washing machine reaches its end-of-life after approximately 12 years, whereas in the pay-per-wash model, the washing machine is taken back by the producer and recycled.

B.3.3. Utility, value and rebound effects – 'how well'

Additional – Besides the actual function of the systems that is captured in the functional unit, a system can also fulfil other non-functional utilities, subjective values and consumption factors. How does the consumer perceive the PSS for example? Another example is 'the feeling of freedom' and 'value of ownership' one can experience from owning a car, instead of sharing a car. Kjaer et al. (2017) provide a list of consumption factors that can be used as inspiration to identify the relevant factors for the systems under study: money, time, space, technology, skills, information, access, convenience/comfort, risk and safety and perception/image.

In this research, several consumption factors can be identified. The absence of ownership could lead to more reckless behaviour, because the consumer feels less responsible for the washing machine. This could potentially lead to more breakages and a reduced lifetime, but, is there really proof for this? Furthermore, consumers could save money by the pay-per-wash model, because no large investments or maintenance costs are needed. Also, when the laundry is done less often due to the economic incentive of paying per wash, more money is saved. The saved money could be spend on other consumer goods, which can result in more environmental impacts (rebound effects). On the other hand, a pay-per-wash model could also be more expensive in the long run, because consumer are never 'finished' with paying for their washing machine. This issue is especially seen when leasing consumers goods or renting houses. Lastly, the perception or image of a pay-per-wash model could play a role in the acceptance of consumers. The consumer acceptance of PSS is widely studied, but is out of scope for this research.

B.4. Process mapping

B.4.1. Flowchart

Flowcharts as shown in the main text.

B.4.2. System boundary

Additional - Kjaer et al. (2017) advice to identify if any processes can be left out of the LCA. There are two types of situations in which a process can be left out. First, unaffected processes, that are equal in both alternatives. Second, cut-off criteria that are assumed to contribute a minor share to the overall impact. For example, administration services and buildings are often cut-off. However, Kjaer et al. (2017) warn that such services or buildings could contribute a significant share for PSS, due to their service character. Therefore these should be kept within the system boundary.

In this study, it was considered to leave out the production process of the washing machine and thus to perform a gate-to-grave LCA, because exactly the same washing machine is operated in both systems. However, in dialogue with the supervisors of this study, it was decided to leave to production in, because the lifetime of the washing machine would be easier to parameterise and data would be available anyway. The cut-offs are stated in the main text.

B.4.3. Impact categories

Impact categories as described in the main text.

B.5. Quantification

B.5.1. Data gathering

Data as described in section 5.3.3 and Appendix C.

B.5.2. Calculations

Calculations as provided in Appendix C.

Appendix C: Data assumptions, calculations and sources baseline scenario

Data collection

The data collection of this LCA was initially set up around the data that Gorenje provided. This consisted out of several documents and reports (as part of the ReCiPSS project) and the results of a fast-track LCA that was performed in 2015. These documents formed the input to the first draft of the involved processes in both systems and their related inputs and outputs. The draft of the product systems was discussed with and verified by Gorenje employees Dr. Aleš Mihelič *(Head of pre-development of R&D Laundry Care Competence Centre)* and Simon Kotnik *(Project Manager)*.

Data on the production process of the washing machine was provided by a bill of materials (included in a confidential Appendix for graduating committee only), originating from the fast-track LCA. Doubts and considerations on choices and assumptions that were made in that LCA were discussed with Farazee Mohammad Abdullah Asif. He works at KTH Royal Institute for Technology, in Stockholm, Sweden and was actively involved in the fast-track LCA. The bill of materials was leading for the production process in this LCA. Some other choices and assumptions were made, after gaining better understanding of the bill of materials. These choices are described below. At a late stage in the LCA, Gorenje provided an updated bill of materials for the ASKO W4086C washing machine, that excluded the techniques that are used for the various materials. This bill of materials (also included in the confidential Appendix for the graduating committee) was thus only used for calculating the transport distances, see the paragraph *Transport* below.

Appendix C.1: Sales

C.1.1. Production

The washing machine is produced in Velenje, Slovenia (A. Mihelič, personal communication, 29 September 2020). All data on the production of the washing machine is based on the bill of materials that was constructed as part of the fast-track LCA (Volders et al., 2014). This bill of materials and the LCA report are confidential, as part of the ReCiPSS project. A washing machine was disassembled and its parts were indicated and weighted at KTH Royal Institute of Technology in Stockholm, Sweden. Farazee Mohammad Abdullah Asif was part of the team who disassembled the washing machine back then, to construct the bill of materials. That bill of materials was approved by Aleš Mihelič (F. Asif, personal communication, 16 October 2020). Several experts in the field of product engineering were present, to judge the type of material and its technology of production, among others Dr. Ir. S. F. J. (Bas) Flipsen from the TU Delft (F. Asif, personal communication, 16 October 2020). Parts smaller than 5% of the total mass of the washing machine were excluded from the fast-track LCA (F. Asif, personal communication, 16 October 2020) and thus also not included in the provided data.

Ecoinvent processes

Several assumptions on the selection of ecoinvent processes were made:

- When the bill of materials indicated any type of steel, ‘market for steel, low-alloyed’ was chosen.
- When the bill of materials indicated steel forming, folding, pressing or punching, ‘deep drawing, steel, 10000 kN press, automode’ was chosen. Deep drawing was assessed by Bas Flipsen as a good indicator for all steel forming techniques (F. Asif, personal communication, 16 October 2020).
- Extrusion of steel is assumed to be ‘impact extrusion of steel, hot, 1 strokes’, since hot extrusion is most common for steel and no information was found on the number of strokes.
- The pump motor in the washing machine is 25W (Gorenje-spares.co.uk, n.d.), but such a motor was not in the ecoinvent database. Therefore 0.625 of a 40W pump was assumed.
- ‘Market for printed wiring board, surface mounted, unspecified, Pb free’ was chosen for the printed wiring board of the machine. Lead free is required within Europe (Tempo Automation, 2019a), surface mounted was assumed since this is cheaper for large appliances (Tempo Automation, 2019b). This type of printed wiring board was later confirmed by Gorenje (S. Kotnik, personal communication, 21 October 2020).
- The weight of the motor was known (6.4 kilograms). The ‘market for electric motor, vehicle’ was used as a proxy.
- The wood support for packing was known to be made of spruce, therefore ‘softwood forestry, spruce, sustainable forest management’ was chosen. The location (Germany) was chosen because of its proximity to Slovenia, the Netherlands, Denmark and Austria.
- The outlet rubber is made of EPDM (ethylene propylene diene monomer) rubber. This is modelled as synthetic rubber in Activity Browser.

Transport

The transport distances are known for some components in the production process, but not for all. If the location of the component was not known, the market in ecoinvent was chosen. From the components of which the location is known, Gorenje produces some components inhouse and orders some components and materials at various suppliers around the world. For the components and materials suppliers that were known, the corresponding location of the ecoinvent process was chosen (i.e. RER, RoW, GLO, Europe without Switzerland). Transport distances were calculated at https://sea-distances.org/ (ship) or https://www.google.com/maps (truck, shortest route). If transported by ship, the transport distance between the city and harbour was neglected. All calculations regarding the transport are shown in table C1 below.

Table C1: Production locations and transportation calculations of production materials and parts, see next page

	From			To							
	City	Harbour (if applicable)	Country	City	Harbour (if applicable)	Country	By	Distance (km)	Weight (kg)	Weight (tonnes)	tkm
Upper cover	Gwangyang	Yeoso	South Korea	Velenje	Koper	Slovenia	Ship	14100	2.555	0.00256	36.026
Water hose-inlet	Gorla Maggiore		Italy	Velenje		Slovenia	Truck	622	0.200	0.00020	0.124
Back cover	Kosice		Slovakia	Velenje		Slovenia	Truck	691	1.510	0.00151	1.043
Front cover	Gwangyang	Yeoso	South Korea	Velenje	Koper	Slovenia	Ship	14100	3.800	0.00380	53.580
Sealing ring	Vrhnika		Slovenia	Velenje		Slovenia	Truck	97	0.206	0.00021	0.020
Back bar middle	Kosice		Slovakia	Velenje		Slovenia	Truck	691	0.808	0.00081	0.558
Back Bar Top	Kosice		Slovakia	Velenje		Slovenia	Truck	691	1.102	0.00110	0.761
Front cover	Cadiz		Spain	Velenje		Slovenia	Truck	2649	0.252	0.00025	0.668
Balancing weight up	Baranovichi		Belarus	Velenje		Slovenia	Truck	1413	5.000	0.00500	7.065
Balancing weight down	Baranovichi		Belarus	Velenje		Slovenia	Truck	1413	5.000	0.00500	7.065
Glass	Milan		Italy	Velenje		Slovenia	Truck	588	1.280	0.00128	0.753
Window front cover	Gorla Maggiore		Italy	Velenje		Slovenia	Truck	622	0.240	0.00024	0.149
Shock absorber	Nurnberg		Germany	Velenje		Slovenia	Truck	640	0.808	0.00081	0.517
Drum (steel)	Gwangyang	Yeoso	South Korea	Velenje	Koper	Slovenia	Ship	14100	5.390	0.00539	75.999
Door holder support	Kosice		Slovakia	Velenje		Slovenia	Truck	691	0.700	0.00070	0.484
Heater	Hangzhou	Shanghai	China	Velenje	Koper	Slovenia	Ship	13745	0.230	0.00023	3.161
Bearings	Landskrona		Sweden	Velenje		Slovenia	Truck	1458	0.410	0.00041	0.598
Motor	Kyoto	Osaka	Japan	Velenje	Koper	Slovenia	Ship	14482	6.400	0.00640	92.685
Tube	Kranj		Slovenia	Velenje		Slovenia	Truck	104	0.300	0.00030	0.031
Pump motor	Sandrigo		Italy	Velenje		Slovenia	Truck	404	0.500	0.00050	0.202
Feet	Naklo		Slovenia	Velenje		Slovenia	Truck	111	0.380	0.00038	0.042
Selection keys	Cadiz		Spain	Velenje		Slovenia	Truck	2649	0.100	0.00010	0.265
Side panel	Gwangyang	Yeoso	South Korea	Velenje	Koper	Slovenia	Ship	14100	4.000	0.00400	56.400
Electronics (basic)	Qingdao	Qingdao	China	Velenje	Koper	Slovenia	Ship	14109	0.900	0.00090	12.698
Electronics (Wi-Fi)	Qingdao	Qingdao	China	Velenje	Koper	Slovenia	Ship	14109	0.930	0.00093	13.121

C.1.2. Use

Transport

The washing machine gets transported from Velenje to Utrecht in a 16-32 metric ton lorry, from Velenje to Utrecht (1250 kilometres). Utrecht is the assumed town of residence of the average household in this LCA. The number of ton-kilometres for the transport is 7.81, see the calculation table below.

	From		To								
	City	Country	City	Country	By	Distance (km)	Weight (kg)	Weight (tonnes)	tkm	Lifetime	tkm / lifetime
Use	Utrecht	Netherlands	Duiven	Netherlands	Big truck	1250	75	0.075	93.75	12	7.8125

Number of laundry cycles

There is no one answer to the question how many laundry cycles an average household runs per year. Numbers range from 365 laundry cycles per year (Amasawa et al., 2018) to 165 laundry cycles per year (Moon et al., 2019). Numbers are hard to compare, since all studies concern different locations and household sizes. Schmitz and Stamminger (2014) analyse 2,000 households in 10 European countries, but the Netherlands is not one of them. They find an average of 197.6 cycles per year. According to Schmitz and Stamminger (2014), one washes 1.3 times per week person, so a household with four persons would run 270 laundry cycles per year. Bracquené et al. (2020) run two scenarios; one with 220 laundry cycles per year (Boyano Larriba et al., 2017 as cited in Bracquené et al., 2020) and one with 250 laundry cycles per year (Stamminger et al., 2018 as cited in Bracquené et al., 2020). Boldoczki et al. (2020) also follow the study by Boyano Larriba et al. (2017). Tecchio et al. (2019) observe 3-4 laundry cycles per week, which would result in 156 to 208 laundry cycles per year. Wasserbaur et al. (2020) assume 167 laundry cycles per year (Pakula & Stamminger, 2010 as cited in Wasserbaur et al., 2020). Lastly, Bocken et al., (2018) find an average of 154.8 laundry cycles per year (12.9 per month); but note that 64% of their respondents are single-person-households.

It was decided to assume 220 laundry cycles per year, because it is in the middle of all numbers found above and two recent studies (Boldoczki et al., 2020; Bracquené et al., 2020) also assume this number.

Washing programme, load and temperature

The maximum load capacity of the ASKO W4086C is 8 kilograms (ASKO, n.d.). Consumers claim to always use the full load of the washing machine (Schmitz & Stamminger, 2014). It was therefore assumed that all laundry cycles are full loads. Under- and overloading of the washing machine is out of scope of this research. (Mixed) cotton and cotton are the most frequently used washing programmes (Schmitz & Stamminger, 2014), this programme is called standard cotton at the ASKO W4086C (ASKO, n.d.) and was assumed to be the only used washing programme in the baseline scenario for the sake of simplicity. The standard cotton programme runs at 40°C, this is in line with the most frequently used washing temperature as reported by consumers (Schmitz & Stamminger, 2014) and the average observed temperature of 40.2°C in the HOMIE case (Bocken et al., 2018).

Electricity and water use

The standard cotton programme use 1.3 kWh electricity and 73 litres of water (ASKO, n.d.). This is a lot more than the numbers that were used in the original LCA in the ReCiPSS project (0.145 kWh of electricity and 45.51 litres of water).

Detergent

Detergent consists out of zeoliter, anionic surfactant and water, in the proportion 0.3 : 0.15 : 0.55 (Volders et al., 2014). The detergent use of 0.08 kilograms per laundry cycle was followed based on the LCA of Volders et al. (2014). This is slightly more than the number used in Amasawa et al. (2018), who assume 0.049 kilograms per laundry cycle for home laundry and 0.082 kilograms per laundry cycle when the laundry is done in a laundromat. Over- and underdosing are out of scope of this research, just as auto-dose and the use of fabric enhancer.

C.1.3. End-of-life

Lifetime of the washing machine

The lifetime of washing machines seems to have been decreasing over the past twenty years. Bakker et al. (2014) observed that the lifetime of washing machines reduced from 12.1 years in 2000 to 11.7 years in 2005. Bracquené et al. (2020) assumed the lifetime of a washing machine to be 10 years. Tecchio et al. (2018) observed that consumers dispose of their washing machines after 12.6 years, either being broken or not. This comes close to the 12.3 years of Boldoczki et al. (2020). The numbers of Tecchio et al. (2019) and Boldoczki et al. (2020) were rounded to 12 years, which was assumed to be the lifetime of the sales model.

As already stated in chapter 3, section 3.2, products are nowadays sometimes discarded or recycled before their physical or economical end-of-life, due to quickly changing technologies, shifting consumer preferences and strong market competition (Khan et al., 2018). Tecchio et al. (2019) state that the primary reason for appliance sales is replacement after product failures. They studied the reasons of consumers not to repair their washing machine and ultimately distinguished between three reasons: 1) consumer choice, when consumers judge the costs of spare parts and labour as too high, 2) technically infeasible, when technical obstacles (like lack of spare of parts or ineffective design for disassembly) hinder repair and 3) non-viable, when service engineers advise consumers to discard the appliance, since it is for example likely to fail again. 78% of unrepaired washing machines was 'consumer choice', 15% was 'technically infeasible' and 7% was 'non-viable'. This indicates that although repair of defective washing machines is still technically feasible, consumers choose not to repair their washing machine because they are discouraged by the related costs, which could limit the lifetime of washing machines.

Waste streams

Specific recycling data for the Netherlands is missing in ecoinvent. Therefore, the end-of-life of the washing machine was simplified to consist out of five waste streams, following Volders et al. (2014). The washing machine in Volders et al. (2014) weighs 67 kilograms. The table below shows the proportion of the waste streams. These proportions (together with the lifetime) are used to calculate the weight of the waste stream as shown in table 6 in the main text

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steel and cast iron	49.6	kg	0.740
Plastics, Teflon, rubbers	8.282	kg	0.124
e-waste	7.56	kg	0.113
packaging cardboard	0.266	kg	0.004
glass	1.28	kg	0.019
	66.988	kg	1

Appendix C.2: Pay-per-wash

C.2.1. Production

Wi-Fi

Exactly the same washing machine is used for the pay-per-wash model (as for the sales model), only the Wi-Fi is added. For the sold washing machine, a smaller piece of electronics would in principle suffice (0.90 kg, as indicated in the bill of materials). The PPW washing machine is equipped with software and Wi-Fi; the size of this printed wiring board was provided by Gorenje's bill of materials (0.93 kg). The printed wiring boards are ordered from China. The Wi-Fi component is modelled in the Activity Browser with the ecoinvent process: market for printed wiring board, surface mounted, unspecified, Pb free [GLO] (Wernet, n.d.).

All other assumptions and sources regarding the production and transport, as discussed in section C.1.1, also apply to this process.

C.2.2. Use

Transport

The washing machine gets transported from Velenje to Utrecht in a 16-32 metric ton lorry, from Velenje to Utrecht (1250 kilometres). Utrecht is the assumed town of residence of the average household in this LCA. The amount of ton-kilometres for the transport is 3.91, see the calculation table below.

	From		To								
	City	Country	City	Country	By	Distance (km)	Weight (kg)	Weight (tonnes)	tkm	Lifetime	tkm / lifetime
Use	Utrecht	Netherlands	Duiven	Netherlands	Big truck	1250	75	0.075	93.75	24	3.90625

Number of laundry cycles, washing programme, load, temperature, detergent, electricity and water use

The number of laundry cycles, the washing programme, load, temperature, detergent, electricity and water use are all exactly the same for the pay-per-wash model as for the sales model (see section C.1.2 for the discussion and sources).

C.2.3. Repair

Component to be repaired

Tecchio et al. (2019) studied the lifetime and recurring failures of washing machines. They found that the electronics (1328 times), shock absorbers and bearings (1301), doors (1086), carbon brushes (914) and pumps (711) most often break down. However, not all components get repaired and therefore it is useful to look at the highest repair rate: the times a component gets repaired / total failures. The highest repair rates were found for doors (80%), carbon brushes (70%) and removal of foreign objects (92%). Noteworthy are the combinations of a high failure number with a relatively low repair rate: electronics (1328 failures, 50% repaired) and shock absorbers and bearings (1301 failures, 50% repaired). The lowest repair rate was found for the drum and tube: 30% (240 failures).

In a meeting with ATAG's (Gorenje's daughter company) service centre in the Netherlands, it was mentioned that the electronics and pump are most often replaced in their experience (J. van Os & M. van Kippersluis, personal communication, 21 October 2020). This was approved by an employee of Gorenje's service centre, who stated that the electronics most often break down, followed by pumps, smaller mechanical parts and shock absorbers (M. Grešovnik, personal communication, 27 October 2020). Out of all the customers that call for a maintenance appointment or repair, 80-90% can be solved by the service engineer at the customer's home (J. van Os & M. van Kippersluis, personal communication, 21 October 2020). These are minor issues, and can be regarded in line with what Tecchio et al. (2019) call 'removal of foreign objects'. 10-20% of all issues needs to be fixed at a repair centre, most often the electronics or the pump. The electronics is the most occurring failure in Tecchio et al. (2019), followed by the pump in fifth place (711 failures).

Most failures occur in the first two years of the service contract, which is in theory explained by the so-called 'bathtub curve'. Only 8-9% of the customers experiences a failure in the first two years (J. van Os and M. van Kippersluis, personal communication, 21 October 2020). Furthermore, a document from Gorenje on expected service intervals (included in confidential Appendix) reveals that only the sealing ring and heater certainly need a replacement, after 4000 washing cycles. These 4000 washing cycles are after the measurement of the functional unit of this research (220 washing cycles x 10 years = 2200 cycles). It is thus likely that a repair occurs less often than once per 4 years, that is why this repair scenario can be regarded a worst case scenario.

It was therefore decided that it would be likely that not more than one component breaks down and needs a repair. The pump motor was chosen in the baseline calculation (other repairs are added as sensitivity analysis), because the electronics showed relative high impacts due to the printed wiring board.

C.2.4. Refurbishment

Components to be refurbished

Since the washing machine is designed to last, Gorenje does not expect to refurbish many and major components (A. Mihelič, personal communication, 21 October 2020).

The heater, pulley and bearings are assumed to be refurbished. The heater needs replacement after 4,000 laundry cycles (A. Mihelič, internal communication, 27 October 2020). The pulley and drive belt are likely to require refurbishment (A. Mihelič, internal communication, 27 October 2020). The bearings are the second most component that breaks down (Tecchio et al., 2019) and need replacement after 8,000 laundry cycles (see document on service intervals in confidential appendix). The assumed refurbishment scenario of refurbishment 1 heater, 0.5 pulley and 0.5 bearings per 4 years was confirmed by Gorenje (A. Mihelič, personal communication, 24 November 2020).

C.2.5. End-of-life

Lifetime of the washing machine

Gorenje claims that the washing machine is 'build to last' and could last 30,000 washing cycles. Having 220 laundry cycles per year this would result in a lifetime of (30,000 laundry cycles per year / 220 laundry cycles =) 136 years. The author of this research found that too optimistic to assume, since that seems only realistic in an industrial setting like a hotel or laundromat, where a washing machine would be in operation 12 hours per day, 7 days a week (12 hours per day * 365 days a year * 10 years = 43,800 laundry cycles).

Since this part of the LCA is performed ex-ante, no real data on the lifetime of the pay-per-wash model is known. Gorenje expects to serve at least six different customers with one washing machine (A. Mihelič, personal communication, 21 October 2020). Customers are expected to have a Silver subscription of 4 years. This is also the median subscription duration. This brings the assumed lifetime of the pay-per-wash model at 24 years (6 customers * 4 years per customer).

Waste streams

The end-of-life of the pay-per-wash model was simplified to consist out of five waste streams, like the sales model. The weight of the waste streams is shown in table 6 in the main text.

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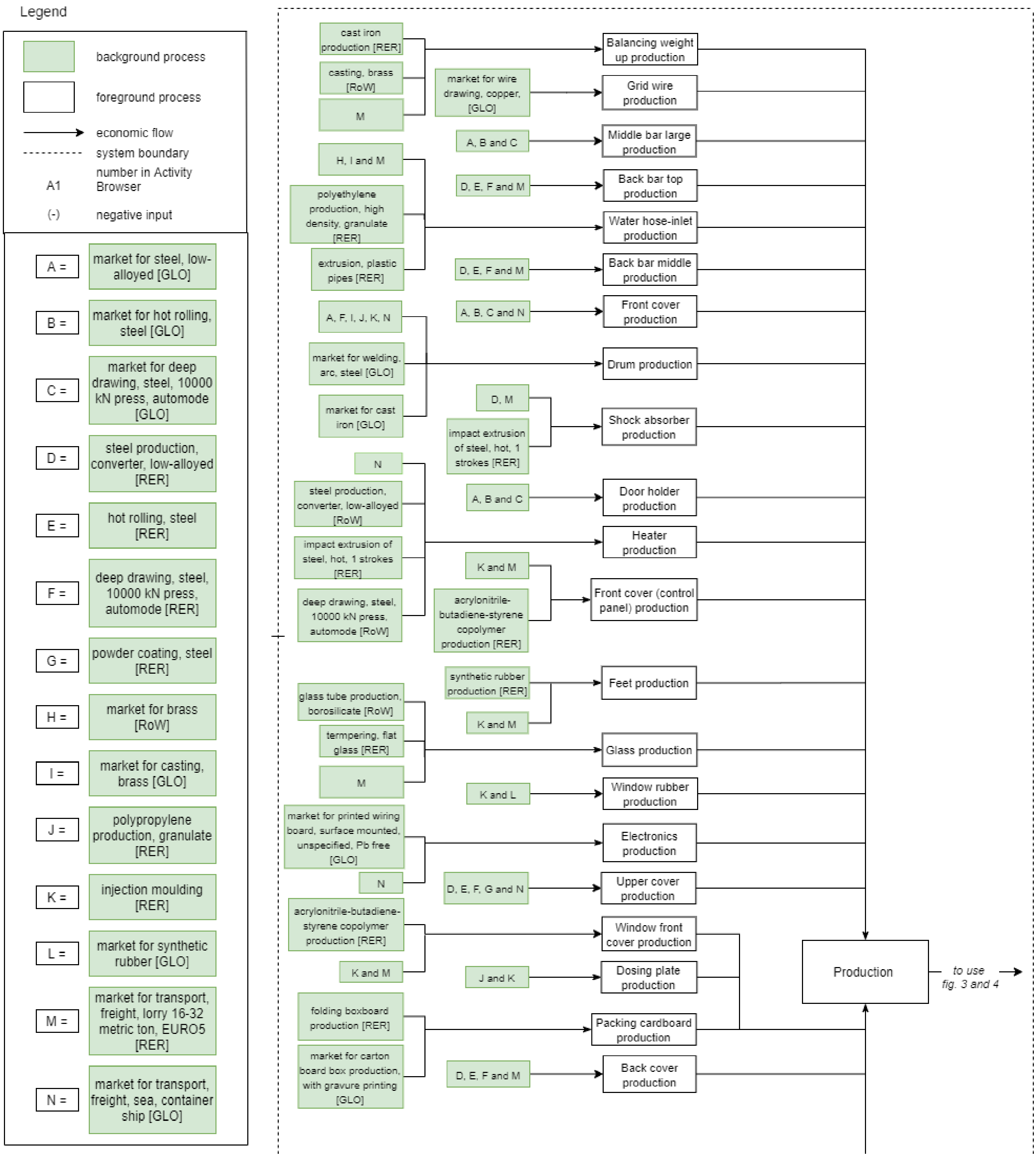
Appendix D: Flowchart of the production of a washing machine
(continues on the next page)



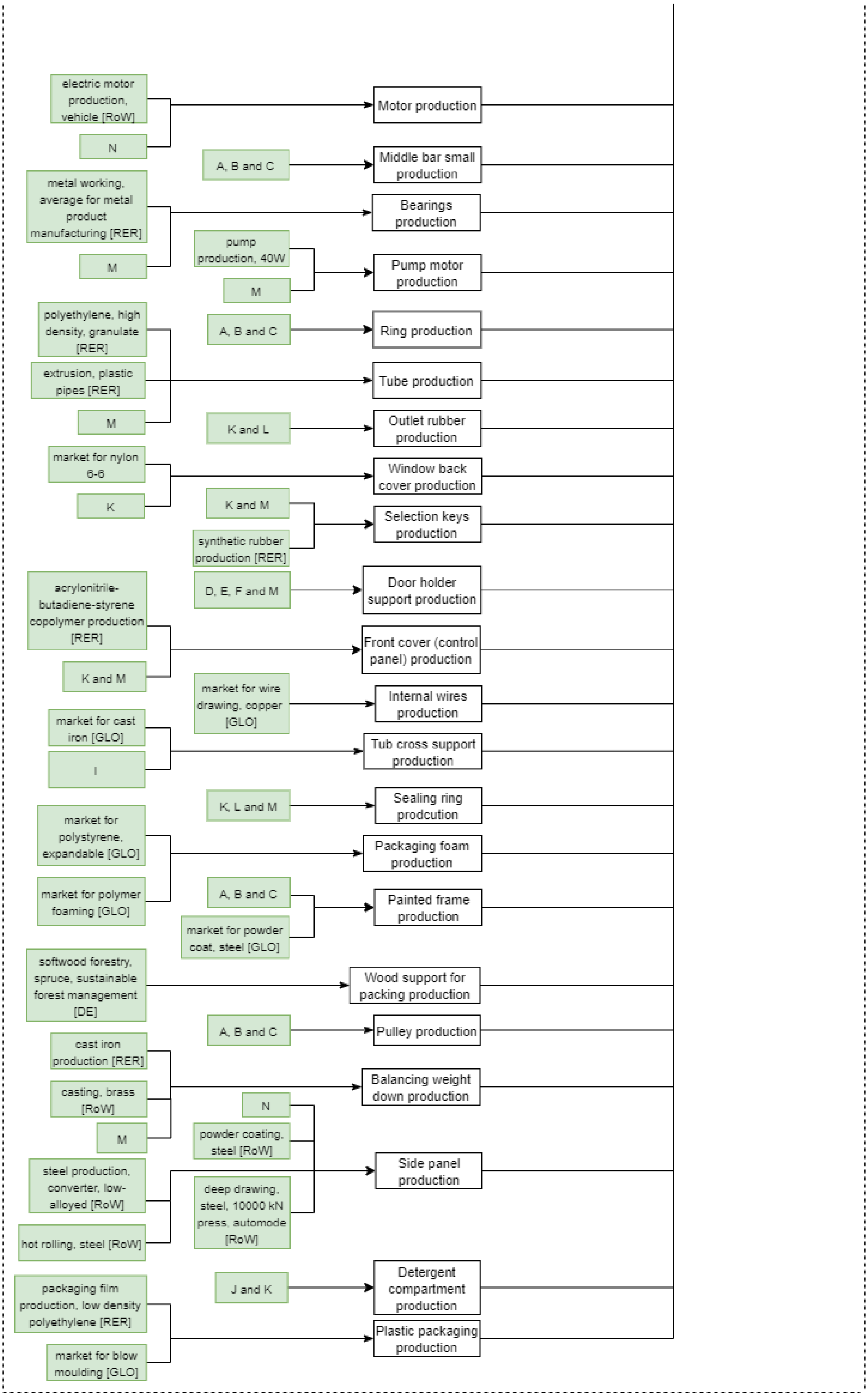


Figure D1: flow chart of the production of a washing machine

Appendix E: Data assumptions and sources user types

Number of laundry cycles

Schmitz and Stamminger (2014) found that the average number of laundry cycles per person per year is 1.3, based on an European average in the year 2011 (n = 2290). This is lower than the numbers that Kruschwitz et al. (2014) found in a study on German consumer behaviour (n = 2867). They reported 2.2 laundry cycles per week for a 1-person-household, 3.4 laundry cycles per week for a 2-person-household, 4.8 laundry cycles per week for a 3-person-household and 5.3 laundry cycles per week for a 4-person-household. Laitala et al. (2012) reported even higher numbers for a similar study in Norway.

User types A and B include numbers of laundry cycles 'on the low side'; 1.3 and 2.6 respectively and user types C and D include numbers 'on the high side'; 5.3 and 3.4 respectively. The lower numbers for user types A and B are chosen because user type A does not want to or does not have the time to do the laundry often and user type B has care for the environment in mind and so will not do the laundry often. The higher numbers for user type C and D are chosen because user type C has a lot of laundry to do with the larger household size and user type D cares about hygiene and is therefore likely to do the laundry more often.

Washing programme

Standard cotton is the most used washing programme (Schmitz & Stamminger, 2014), this is reflected in the percentages for scenarios B, C and D. Standard cotton is followed by easy care, synthetics and wool/hand wash (Schmitz & Stamminger, 2014). The easy care programme is also used by three user types most likely to use it: user types A, B and C – user type D would think this programme does not clean the laundry enough. Every user type is assumed to use three washing programmes. For user type A this is easy care and hand wash, since these are among the most used washing programmes according to Schmitz and Stamminger (2014), supplemented with washing programme quick, because this fits the characteristics of user type A. The three washing programmes for user type B are standard cotton (eco) since this is the most used washing programme and Eco 40-60 and quick, because user type B would choose these programmes with care for the environment in mind. User type C is an average family and as such follows the most used washing programmes as found by Schmitz and Stamminger (2014): standard cotton, easy care and hand wash. User type D uses standard cotton and easy care, because these are among the most used washing programmes (Schmitz & Stamminger, 2014), supplemented by hygiene, because of the hygienical concerns of user type D.

Temperature

40°C is the most used washing temperature, followed by 30°C and 60°C. Schmitz and Stamminger (2014) report that, on average, 40% of the laundry cycles is done at 40°C, 30% at 30°C and 30% at 60°C. This division is followed for user type C. User type A is therefore also assumed to wash most often at 40°C and otherwise colder, since warmer temperature take longer. User type B is also assumed to wash most often at 40°C. User type B does the laundry otherwise in a cold, quick programme (20°C) or uses the eco-programme (Eco 40-60). User type D is assumed to never do the laundry at a colder temperature than 40°C, scared of potential bacteria in the machine and clothes.

Electricity

The electricity consumption is reported in the manual for use of the ASKO washing machine (ASKO, n.d.). The following washing programmes use this amount of electricity:

- Standard cotton (60°C, 'everyday wash'): 1.6 kWh
- Standard cotton + Eco: 0.52 kWh
- Easy care: 0.65 kWh
- Eco 40-60: 0.84 kWh
- Quick: 0.5 kWh
- Hand wash: 0.27 kWh
- Hygiene: 1.8 kWh

Water

The water consumption is reported in the manual for use of the ASKO washing machine (ASKO, n.d.). The following washing programmes use this amount of water:

- Standard cotton (60°C, 'everyday wash'): 75 litres
- Standard cotton + Eco: 54 litres
- Easy care: 60 litres
- Eco 40-60: 56 litres
- Quick: 40 litres
- Hand wash: 58 litres
- Hygiene: 82 litres

References Appendix E: assumptions and sources user types

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