Use-PSS rebound: Carbon footprint reduction potential of clothing rental subscription with consideration of direct economic rebound effect

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Abstract

Use-oriented Product Service Systems (Use-PSS) for clothing (e.g. fashion rental subscription) are often seen as sustainable alternatives for today's wasteful fashion consumption. To increase their market acceptance, emphasis on their relative price advantage is discussed in the literature and public sectors, while the risk of an increase in overall consumption of facilitation of wear offsetting their environmental benefit (i.e. direct rebound effect) has been overlooked in Life Cycle Assessment studies, due to the assumption of constant wear occasions.

Based on literature and using system dynamics as a conceptual virtual laboratory, this study analyzes the market-mediated potential of Use-PSS for women's dress to reduce annual carbon footprint, through simulations of what-if scenarios under various consumer behavior and PSS membership designs.

The results show that; 1) PSS memberships offering unlimited swaps based on flat-rate monthly fees entail high risks of rebound, whereas those offering limited monthly swaps and items accessible while charging for each swap are more robust to consumer behavior and rebound, 2) increased wash cycle frequency could compromise rental garment lifespans and jeopardize the carbon footprint reduction potential, while such risk can be amplified by direct rebound, and 3) multiple wears per rented dress by each user can significantly reduce the risk of rebound and lifespan shortening.

The findings highlight the potential significance and the need for empirical research of the direct economic rebound effect and the effect of wash cycle frequency on rental garment lifespan. Practical recommendations are to; 1) apply public incentives such as reducing the value-added tax rate, only for PSS platforms offering limited monthly swaps and items accessible while charging for each swap and 2) enhance the unique attractiveness of clothing PSS rather than its price competitiveness, via fostering word of mouth from subscribers, adopting high-quality and sustainable material, and personal style consultancy service.

Keywords: Product Service Systems; Life Cycle Assessment; clothing rental subscription; system dynamics, replacement rate; rebound effect; phantom wear

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Nijmegen, March 16th 2021

Five years ago, I dreamed of a far-off place to learn systems thinking as an Erasmus master, which seemed out of my reach back then. Today, I am more than grateful and honored to be able to fulfill my ambition thanks to the blessings that carried me all the way to now.

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Yoshitaka Miura

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List of Abbreviations

- CEAP: Circular Economy Action Plan
- CFC: Collaborative fashion consumption
- CPW: Cost per Wear
- CW: Constant Wear (scenario)
- IPW: Impact per Wear
- LCA: Life Cycle Assessment
- PSS: Product Service Systems
- SD: System Dynamics
- SOS: Subscription-based online services
- UM: Utility Maximization (scenario)
- VAT: Value Added Tax
- WPS: Wear per Swap (per rented dress)

Chapter 1. Introduction

1.1 Background

Clothing is a fundamental part of our everyday life and at the same time, its industry is one of the most polluting, responsible for around 4 percent of the global total annual carbon footprint (Berg, Granskog, Lee, & Magnus, 2020) which is more than international flights and maritime shipping combined (Ellen MacArthur Foundation, 2017), while generating other significant environmental pressure in terms of water consumption, resource depletion, microfiber release, and chemical toxicity. These impacts are projected to increase along with the growing trend of population and income level, and even with the current pace of decarbonization efforts, the industry is likely to miss the 1.5°C pathway of the Paris agreement by 50% (Berg et al., 2020).

One important background for this is the trend of decreasing clothing utilization (i.e. the number of times a garment is worn) reinforced by a continuous drop in price and the fast fashion phenomenon, where we buy significantly more clothes (e.g. 40 % increase per average EU citizen between 1996 and 2012 (Šajn, 2019)) but wear much less (e.g. 36% decrease globally) than 15 years ago (Ellen MacArthur Foundation, 2017), resulting in an ever-higher production rate that mainly drives the environmental impact of today's clothing sector.

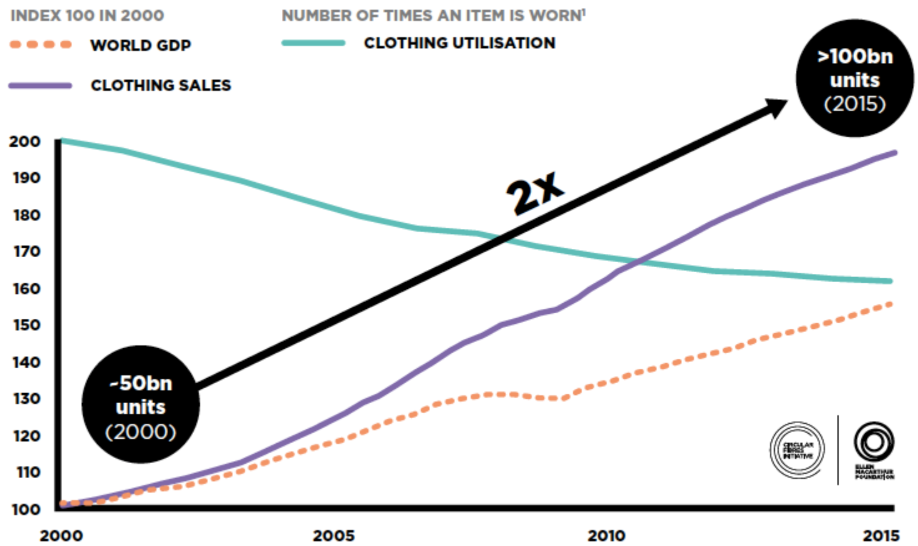

Figure 1 Growth of clothing sales and decline in clothing utilization since 2000 [1]

According to a UK consumer survey (WRAP, 2017), the major reasons for clothing disposal are "size and fit" (42%) and "not liking anymore" (26%), while physical wear and

[1] Adapted from: Copyright © Ellen MacArthur Foundation, *A New Textiles Economy: Redesigning fashion's future*, p.18, (2017)

tear accounts only for 9%, highlighting today's massive underutilization and premature disposal of clothing (Ellen MacArthur Foundation, 2017), a significant room for improvement in environmental impact by extending the active clothing lifespan. For example, if all clothes in Sweden were used twice as long, it would mitigate the annual carbon footprint nearly by half, however, this also requires businesses and consumers to sell and buy less (Sandin, Roos, Spak, Zamani, & Peters, 2019) on top of compromising in fulfilling consumers' desire for change and novelty which are fundamental values in fashion (Armstrong, Niinimäki, Kujala, Karell, & Lang, 2015), posing a significant challenge for policy such as design for longevity (Cooper et al., 2013) under the current linear, "take-make-disposal" (Ellen MacArthur Foundation, 2017:36)) business model.

Meanwhile, Product Service Systems (PSS) is recently gaining business and political attention (Cerulli-Harms et al., 2018) as a promising alternative business model to realize Circular Economy also for the clothing industry (Cerulli-Harms et al., 2018; Kjaer, Pigosso, Niero, Bech, & McAloone, 2018). With the core idea of providing "a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs" (Tukker & Tischner, 2006:1552), PSS facilitates repair, recycle, sharing, renting, and leasing services while incentivizing businesses to improve in product quality, longevity, and natural resource independence (Cerulli-Harms et al., 2018) while also satisfying the desire for novelty and variety through sharing with multiple users (Boger et al., 2017).

Clothing library and fashion rental platforms where "customer signs a package to withdraw a certain number of pieces of clothing for a short period of time" (Santos, Campos, & Miguel, 2019:858) are examples of Use-oriented PSS (Use-PSS) (Tukker, 2015) for clothing, which have gradually grown in number since their emergence in the early 2010s. The market is expected to continue to grow further (Shrivastava, Jain, Kamble, & Belhadi, 2021), reinforced by advances in e-commerce technology that makes online fashion renting more convenient and accessible (Lee & Chow, 2020). Successful examples include Rent the Runway in the US and Girl Meets Dress in the UK that have both grown to multi-million dollar businesses, drawing the attention and anxiety of major fashion retailers (Lee & Chow, 2020). They offer attractive services to fashion-conscious users including unlimited rentals under a fixed monthly subscription fee (Mukendi & Henninger, 2020) while strongly advocating more sustainable fashion (Lee & Huang, 2020) compared to the conventional sales model.

However, how much in fact clothing PSS can reduce the environmental impact is not entirely clear, since an increased transportation impact by frequent shipping can outweigh the environmental benefit gained by the avoided production (Johnson & Plepys, 2021; Zamani, Sandin, & Peters, 2017) and the lifespan of garments has to be sufficiently extended (Piontek, Amasawa, & Kimita, 2020; Zamani et al., 2017). Moreover, since clothing PSS typically offers an economic advantage over the conventional sales model, saved expenditure of consumers could induce additional spending on goods and services, posing a risk of rebound effects (Iran & Schrader, 2017; Kjaer, Pigosso, Niero, et al., 2018) which are side effects that offset the environmental benefit because of behavioral or systemic responses (Kjaer, Pigosso, & McAloone, 2017). Studies regarding environmental potential of Use-PSS for clothing based on Life Cycle Assessment (LCA), a scientific methodology to quantify environmental impacts of products and services (Kjaer, Pagoropoulos, Schmidt, & McAloone, 2016), so far have not incorporated potential rebound effects nor the effect of price on replacement rate (Johnson & Plepys, 2021; Piontek et al., 2020; Zamani et al., 2017), because of assuming constant demand of consumption (Girod, De Haan, & Scholz, 2011) of wearing clothes.

This limitation is however relevant when considering the current key challenge of low market penetration of clothing PSS and related public interventions. The new European Circular Economy Action Plan (CEAP) specifically aims to drive new business models in the textile sector "in particular by providing incentives and support to product-as-service models, circular materials and production processes" (European Commission, 2020:13). Among the policies considered, reducing Value Added Tax (VAT) rate for clothing PSS is featured as one powerful assistance to stimulate circular business models of clothing, as it allows lowering the prices and enables to better compete with conventional products and services (Ecopreneur.eu, 2019; Elander, Watson, & Gylling, 2017). Inspired by Sweden's policy of VAT reduction for repair services of clothing, shoes, and bicycles from 25% to 12% to promote repair, it is also argued that such economic incentives could also be implemented in other EU member states (European Commission, 2020) and also possibly expanded to reuse, sharing, leasing and renting of clothing (Elander et al., 2017; Manshoven et al., 2019).

Under this context, there is a need to increase understanding of what the environmental impact reduction potential of clothing PSS is while accounting for economic rebound effects, which has been the knowledge gap this study aims to address by an explorative study.

1.2 Problem Definition

While clothing PSS could potentially extend the active lifespan of clothes and thus reducing their production and environmental impact, it might also risk that clothing becomes a resource-intensive 'service' (in contrast to conventional purchase of products) when transport frequency and impact are not properly managed, resulting in a problem shifting. Such risk might further increase when using clothing PSS creates economic savings for consumers which could induce rebound effects, however such consideration is absent in the current LCA studies. At the same time, policies to reduce the price of clothing PSS (e.g. via VAT reduction) are discussed in order to overcome its still limited market penetration. As PSS are often viewed as inherently sustainable business models, a stronger consideration of risks including rebound effects could enhance the knowledge of the potential danger and enable companies and public policies to address them better, contributing to further implementation of PSS business models (Blüher, Riedelsheimer, Gogineni, Klemichen, & Stark, 2020), which also motivates this thesis.

1.3 Research Aim and Objective

The main aim of the thesis is first, to increase the understanding of the environmental potential of subscription-based Use-PSS of clothing when economic rebound effects (i.e. market-mediated change in consumption and the resulting degree of substitution) are taken into account, and second, to formulate recommendations for businesses and public sectors to increase the environmental potential of Use-PSS of clothing while mitigating the risk of rebound effects. In order to achieve those aims, the objective of this research is to analyze the potential of Use-PSS for women's dress to reduce the annual carbon footprint while taking economic rebound effects into account, through a system dynamics model of a hypothetical clothing market of women's dress. The model simulates the annual carbon footprint as an outcome of various scenarios demonstrated regarding:

1) Retailers and PSS platforms, who aim to reduce the annual carbon footprint of their businesses by a) switching material to recycled polyester under conventional retail business model, or b) starting monthly subscription-based Use-PSS of dress
2) Consumers in Market A, who purchase dresses at conventional retail or rent them from Use-PSS of dress, under the assumptions that they a) maximize utility under constant expenditure, or b) demand constant wearing of dresses per year

The reason for focusing on women's dress is that it both has a high environmental potential for improvement as well as high demand in clothing PSS. Women's dress is considered as a priority product for reducing environmental impact because of their large amount of sales volume (WRAP, 2017) and a large impact per wear (Sandin et al., 2019). Dresses have a high production impact due to heavyweight and complex production process (Sandin et al., 2019), while typically worn only for short times (Iran & Schrader, 2017; Johnson, 2020), which makes them suited for rental model from an environmental perspective (Piontek et al., 2020). At the same time, from consumers' perspective, dresses are highly fashion-oriented and changes in style matters greatly (Lai, Song, Xu, & Chiu, 2018; Shrivastava et al., 2021) which makes them one of the major garment type currently handled in Use-PSS for clothing.

Admittedly, carbon footprint alone does not capture the full range of environmental impact, and focusing on it solely may risk problem shifting with other impact categories (e.g. water scarcity, land use, toxic substance, fossil resource depletion, etc.) (Laurent, Olsen, & Hauschild, 2012). However, the study focuses only on the annual carbon footprint in order to enable the analysis of rebound effects while effectively capturing the shift in primary impacting life cycle phases (e.g. from production to transport) (Peters, Svanström, Roos, Sandin, & Zamani, 2015; Roos, Zamani, Sandin, Peters, & Svanström, 2016).

1.4 Research Questions

1.4.1 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint?

1.4.1.1 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint when consumers' demand of wear remained constant?

1.4.1.2 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint when economic rebound effects are taken into account?

1.5 Outline of the thesis

The structure of the thesis is as follows. First, Chapter 2 is a literature review of the topic of Use-PSS for clothing, LCA, and rebound effects and explains the theoretical background this study will base on. Next, Chapter 3 describes the methodology applied, explaining the research strategy, data collection, and ethics. Then, the results are presented in Chapter 4 and Chapter 5, where Chapter 4 describes the qualitative analysis based on a Causal Loop Diagram (CLD) which guides the formulation of the quantitative model, and Chapter 5 explains the quantitative analysis of simulation results. Finally, Chapter 6 concludes the thesis by answering the research question, providing discussions of theoretical and practical implications as well as limitations of the study and suggestions for future research.

Chapter 2. Theoretical Background

This chapter provides an overview of the narrative literature review I conducted to map out the key relevant concepts and theoretical frameworks to analyze the topic.

2.1 Types of Product Service Systems for clothing

Product Service Systems (PSS) of clothing is one of the forms of collaborative fashion consumption (CFC) which is a broader concept where clothing is shared and used by multiple users, including second-hand clothing, peer to peer sharing, sharing with friends and families, and PSS (Becker-Leifhold & Iran, 2018). PSS ranges from purely product-based to purely service-based business orientation, which can be categorized as Product-oriented PSS (Product-PSS), Use-oriented PSS (Use-PSS), and Results-oriented PSS (Result-PSS) (Tukker, 2015). Product-PSS refers to a business model mainly based on the traditional sales of products, while related services such as recycling, repair and take back are provided additionally. Use-PSS is a model where services are provided through the products owned by the company, while customers gain the access to use them through an ownership-less consumption in exchange for a certain fee. Result-PSS refer to purely service-based business model such as professional laundry services or style consulting services (Kjaer, Pigosso, Niero, et al., 2018; Tukker, 2015).

2.2 Membership system of Use-PSS for clothing

Use-PSS for clothing consists of diverse services, and three relevant types are summarized below. This thesis focuses on the rental subscription of clothing based on a flat monthly fee (i.e. lease subscription and subscription-based online services) since it provides the largest opportunities for consumers to try out the clothes but also poses the risk of an increase in fashion consumption. These business models typically emphasize convenience as an important attractor, offering free shipping both ways (Niehm, 2020; Tu & Hu, 2018) and professional cleaning.

2.2.1 Short-term rental

Short-term rental of clothing refers to a pay-per-use model, where items are individually priced (at a fraction of retail price) for a given period of time. Examples include clothing for special occasions such as formal wear (Johnson & Plepys, 2021) and sports, as well as the clothing of which their needs change over time due to body size change such as baby clothes, children's clothes, and maternity wear (Petersen & Riisberg, 2017). An important difference from the monthly subscription model is that users can flexibly rent as many items as needed at a time, although they do not have unlimited access to inventory or the right to exchange (Tukker, 2004), therefore an increase in access of items are usually accompanied by an increased rental fee.

2.2.2 Lease subscription

The characteristic of leasing clothing is that the monthly fee is fixed at a flat rate, depending on the maximum items available at a time and frequency of exchange, often allowing the unlimited exchange of items (Tukker, 2004). Hence, users have a limited amount of items they can lease at a time, yet are allowed to frequently exchange them (Ellen MacArthur Foundation, 2017; Pedersen & Netter, 2015). This allows users to fulfill the desire for novelty, variety, and change (Ellen MacArthur Foundation, 2017) with affordable cost and less risk (Pedersen & Netter, 2015), while also relieving customers from the guilt of overconsumption (Armstrong, Niinimäki, Lang, & Kujala, 2016), providing opportunities to try and experiment with styles (Mukendi & Henninger, 2020; Pedersen & Netter, 2015). Ultimately, this model attempts to offer a "Netflix for clothing model where consumers get access to unlimited items" (Boger et al., 2017:100), which is particularly attractive for "fashion-conscious consumers who wear the same clothes with very little frequency (only once or twice) and do not want to spend much money" (Shrivastava, Jain, Kamble, & Belhadi, 2021:3). The only constraint in the unlimited swaps service is the shipping time (Gilliot, 2019), and users can get access to the next set of items as often as they want by sending the previous items back (Strähle & Erhardt, 2017).

2.2.3 Subscription-based online services (SOS) for fashion

Subscription-based online services (SOS) of fashion are "an e-business that provides periodic delivery of a customized box of merchandise directly to the consumer's home for a weekly/ monthly subscription fee" (Woo & Ramkumar, 2018:121). Subscribers give preferences of styles but do not specify the exact items to be shipped nor see all the product offerings (Niehm, 2020). Styling and curation services are then utilized to fit the needs of the users (Niehm, 2020), which adds a hedonic element of surprise (Woo & Ramkumar, 2018) and a chance to broaden the style horizons by exploration (Niehm, 2020; Tao & Xu, 2018). Fashion SOS is particularly popular among busy consumers who want to save time shopping but want to follow fashion trends, such as working professional women (Tu & Hu, 2018). The service reduces users' effort of searching for information, addressing their "decision fatigue" (Woo & Ramkumar, 2018:123). At the same time, retailers can benefit from introducing their products without pressuring consumers while reaching a wide range of consumers (Woo and Ramkumar, 2018) and the end goal is for the users to purchase the items (Park & Joyner Armstrong, 2019). Fashion SOS typically use algorithms and professional stylists to customize selections based on users preference, where some platforms allow users to modify the selection before shipment, while others don't (Gilliot, 2019). While the service provides extra surprise that increases user satisfaction if successful, mismatches between their expectation and actual product quality, fit, and selection are one of the key dissatisfaction factors for the users (Niehm, 2020).

2.3 Life Cycle Assessment of Use-PSS for clothing

Roos et al. (2016) carried out an LCA study to give an overview of the relative environmental potential of possible intervention in the total annual Swedish apparel consumption. A reduction in total consumption due to doubling the lifespan of all garments could save more than half of the carbon footprint and freshwater consumption while replacing all virgin polyester usage with chemically recycled polyester could reduce the annual carbon footprint by 6% (Roos et al., 2016). If 40% of the total annual Swedish apparel consumption (i.e. penetration rate of 40%) could be turned into Use-PSS in physical stores (offline service) or on the internet (online service) whereby the lifespan of clothing can be doubled, the annual carbon footprint could be decreased by 11% if the service was operated online, but also be increased by around 4% when operated offline due to increased private car travel, highlighting the risk of problem shifting and strong dependency on consumer behavior and transportation mode (Roos et al., 2016).

Taking a closer look, Johnson & Plepys (2021), Piontek et al. (2020), and Zamani et al. (2017) identified that the critical factors that affect the environmental outcome of Use-PSS for clothing are the number of times a rented garment is worn per user (i.e. Wear per Swap (WPS), which is also the inverse of the number of total users sharing a rental garment), leverage of lifespan (how much the lifespan of a garment can be extended) and transportation mode and distance. WPS is a significant factor that affects the impact per wear of Use-PSS clothing, since fewer wear per user would mean more customers per garment life cycle and hence more transportation impact (Zamani et al., 2017). Johnson & Plepys (2021) also showed that replacing one wear occasion of purchased formal dress by one offline rental with a high impacting transportation mode (e.g. private car) does not result in environmental benefit because of high transportation impact to facilitate one rental. Roos, Sandin, Zamani, & Peters (2015) and Zamani et al. (2017) showed that, as the best case, if a T-shirt can be used four times longer via an online clothing library with low impact transportation mode (i.e. using bus to a pickup point), it could reduce the carbon footprint by 67%, while on the contrary, as the worst case, if it is used only for twice as long via an offline store with high impact transportation mode (i.e. car), it could instead increase the carbon footprint by 23%.

As such, studies recommend to focus on garment type which has higher leverage for lifespan extension such as infrequently used formal wear (Piontek et al., 2020), to decrease the transportation impact by focusing on online operation and offering low impact shipment options and locating the physical rental stores in urban areas with good public transportation (Johnson & Plepys, 2021; Zamani et al., 2017). Regarding the membership design of PSS platforms, Johnson & Plepys (2021) recommended businesses avoiding a pay-per-single use scheme and Zamani et al. (2017) suggested offering fewer items available per user at a time and a longer lease period, to incentivize users to increase the number of wear per user per rented garment. Further, Zamani et al. (2017) suggested that the number of transportation could be reduced through a payment system where the users have to pay for each transaction of clothing, incentivizing reduced transaction frequency.

While the LCA studies form a credible foundation on the relative impact per wear of PSS clothing compared to a conventional business model, the potential of rebound effects has been disregarded and discussed outside of LCA studies.

2.4 Rebound effect related to clothing

It is often argued that one has to take rebound effects into account when considering the overall environmental benefit of CFC because "Only if CFC substitutes the purchase of new clothes instead of just adding to it, CFC has the chance to contribute to sustainability" (Iran & Schrader, 2017:477). Collaborative consumption can both facilitate a sustainable, less material intense consumption or "a vector for the hyperconsumption" (Demailly & Novel, 2014:8) and therefore its overall sustainability potential is at odds with consumer behavior. Clothing is a highly price-sensitive consumption (Kratena, Meyer, & Wüger, 2009) and consumers' tendency to maximize fashion experience as long as affordable has been witnessed in today's fast fashion phenomena (Niinimäki et al., 2020) as well as in online second-hand clothing market (Armstrong & Park, 2020; Demailly & Novel, 2014). Such risk of hyper-consumption and utility maximization behavior is likely relevant to clothing rental subscription (Lee & Chow, 2020) as one of their primary appeal is that they provide an opportunity to try and experiment with styles (Mukendi & Henninger, 2020; Pedersen & Netter, 2015) to fulfill the desire for novelty and variety at a fraction of cost (Armstrong et al., 2016), which is particularly attractive for fashion-conscious consumers (Shrivastava, Jain, Kamble, & Belhadi, 2021). For example, a fashion SOS platform

Le Tote experienced a high consumption speed of rented items by their customers to such a degree that the platform could hardly follow to satisfy their unceasing craving for novelty and variety of selection (Gilliot, 2019).

The whole concept of rebound effect ranges from microeconomic level (i.e. change in individual consumption) which consists of direct rebound effect (i.e. change in consumption of the same goods and services) and indirect rebound effect (i.e. change in consumption of other goods and services) to macroeconomic level (i.e. change in overall demand as a market and societal response) (Maxwell, Owen, McAndrew, Muehmel, & Neubauer, 2011). Analyzing the potential for direct rebound effect and how to mitigate it helps to identify the cause of the rebound and thus mitigate other indirect effects as well (Kjaer et al., 2017). Rebound effect can occur from any freed resources required for consumption including money, space, time, and phycological factor (e.g. mentally held environmental budget) (Girod et al., 2011).

Consideration of rebound effects in the clothing sector is factored in by the concept of replacement rate, which in the case of second-hand clothing can be defined as “the degree to which the purchase of second-hand clothing and household textiles replaces the purchase of similar new items” (Nørup, Pihl, Damgaard, & Scheutz, 2019:1026). For example, “a replacement rate of 50% means that the purchase of two second-hand items replaces the purchase of one new item” (Farrant, Olsen, & Wangel, 2010:728).

The replacement rate is essentially determined by market forces and users’ perceived value which is a subjective judgment (Kjaer, Pigosso, McAloone, & Birkved, 2018) and therefore challenging to quantify accurately, although it is generally considered that a 1:1 displacement between second-hand clothing and new items is unlikely (Farrant et al., 2010; Fisher, James, & Maddox, 2011). For example, consumer surveys indicate replacement rates of second-hand clothing as 0.6 in Sweden (Farrant et al., 2010) and around 0.7 in the US (Patwary, 2020). By definition, a replacement rate lower than one inevitably means that a provision of second-hand clothing partially adds to the overall supply of clothing (i.e. grow the whole pie) rather than replacing a part of it (i.e. replace a piece of the pie), offsetting the potential to avoid primary production to some degree, a phenomena which Zink & Geyer (2017:593) conceptualized as “circular economy rebound.”

2.5 Circular economy rebound

The concept of circular economy rebound provides a useful framework to analyze the environmental potential of an intervention of circular economic activities (i.e. repair, recycle, etc.) while taking direct rebound effect into account, where it describes the condition to yield a net environmental benefit ($E_{net} < 0$) as follows (Zink & Geyer, 2017:596):

$$E_{net} = e_r * \Delta Q_r + e_p * \Delta Q_p < 0 \quad \textit{which can be expressed as} \quad \frac{e_r}{e_p} < \frac{|\Delta Q_p|}{Q_r}$$

where "e_r and e_p being the environmental impact of producing one unit of secondary (e.g. recycled) and primary (e.g. new) material, respectively, and… ΔQ_r being the change in secondary production and ΔQ_p the resulting, market-mediated change in primary production" (Zink & Geyer, 2017:596). The e_r / e_p corresponds to the relative impact per unit of consumption. For a single unit of clothing, for instance, it is known that a reuse and refurbishing of a garment is by far less impacting than producing a new garment (Sandin & Peters, 2018). The overall environmental impact depends then on the replacement rate, represented by $|\Delta Q_p| / \Delta Q_r$ in the formula. The significance of the formula is that it clearly outlays the necessity that the replacement rate must be greater than the relative impact per unit of consumption, in order to yield a net environmental benefit while taking the direct rebound effect into account. For second-hand clothing, Dahlbo, Aalto, Eskelinen, & Salmenperä (2017) showed that a replacement rate as low as 50% could still yield a net environmental benefit because of the low e_r / e_p, although this type of broader understanding of environmental potential incorporating rebound effects has been still not studied under the context of Use-PSS for clothing.

2.5.1 Circular economy rebound under the context of Use-PSS of clothing

Through the literature review, it was identified that the concept of replacement rate and rebound effects has not yet been conceptualized and investigated under the context of Use-PSS of clothing, even though there could be a risk of increase in facilitation of trial wear and accompanied environmental impacts. Although Zink & Geyer (2017) delimit the concept of circular economy rebound to the activities of reuse, refurbishment, and recycling while ruling out sharing and servicizing of products, its fundamental logic can be also applied under the context of Use-PSS by replacing 'production' with 'provision of use opportunity.' For this reason, I will use the term 'Use-PSS rebound' in this thesis and expand the application of their theory to Use-PSS for clothing as following.

For a Use-PSS for clothing to yield a net environmental benefit compared to a conventional linear business model, the following condition has to be met:

$$E_{net} = IPW_{PSS} * \Delta WPY_{PSS} + IPW_{Linear} * \Delta WPY_{Linear} < 0 \tag{1}$$

with IPW_{PSS} and IPW_{Linear} being the environmental impact per wear of a PSS dress and a linear (i.e. conventionally sold) dress, respectively, while ΔWPY_{PSS} and ΔWPY_{Linear} being the change in number of wear per year of PSS dresses and linear dresses.

The condition to yield an environmental benefit (i.e. $E_{net} < 0$) can be also described as:

$$\frac{Impact\ per\ Wear_{PSS}}{Impact\ per\ Wear_{Linear}} < \frac{|Reduction\ in\ Wear\ per\ Year_{Linear}|}{Increase\ in\ Wear\ per\ Year_{PSS}} \tag{2}$$

where the right part of the formula represents the replacement rate of wear. The current discussion in the literature focuses on the relative impact per wear (i.e. left side of the formula) while assuming a constant replacement rate of wear (i.e. right side of the formula) of one.

A Use-PSS rebound in clothing occurs when one facilitation of wearing a Use-PSS garment does not fully lead to a decrease in purchase rate of linear clothing, that is, when it fails to substitute for one wear of linear clothing, or when it does substitute but at the expense of compromising their utilization. For example, an additional 'back up' formal dress offered to users to mitigate the mismatch of fit (McKinney & Shin, 2016), or in cases of mismatch in fashion SOS where the user dislikes one of the garment in a received box (Niehm, 2020), it would not contribute to substitute for an actual wear occasion which otherwise would have been satisfied through a linear dress (i.e. net increase in demand of wear, as in ***Figure 2***, p.20). However, the facilitation of such wears will still require shipment, packaging, and cleaning cycle, using up the physical lifespan of the garment (Laitala & Klepp, 2020) while causing environmental impact, a phenomenon that may be referred to as a 'phantom wear' (i.e. replacement rate of wear < 1). Or on the other hand, even if one wear of Use-PSS clothing substitutes one wear of linear clothing (e.g. dress, shirt, jeans, etc.) with a replacement rate of wear of one, as long as it does not contribute to reducing the purchase rate of these garments, this would merely mean that the utilization of the pre-owned clothes is compromised, which also offsets the environmental benefit (i.e. effective replacement rate of wear < 1).

Since LCA studies so far assume a constant replacement rate of wear of one and leave out the potential of Use-PSS rebound, this thesis aims to conceptually investigate the change in replacement rate by applying the "consumption-as-usual" approach (Girod, De Haan, & Scholz, 2011:3).

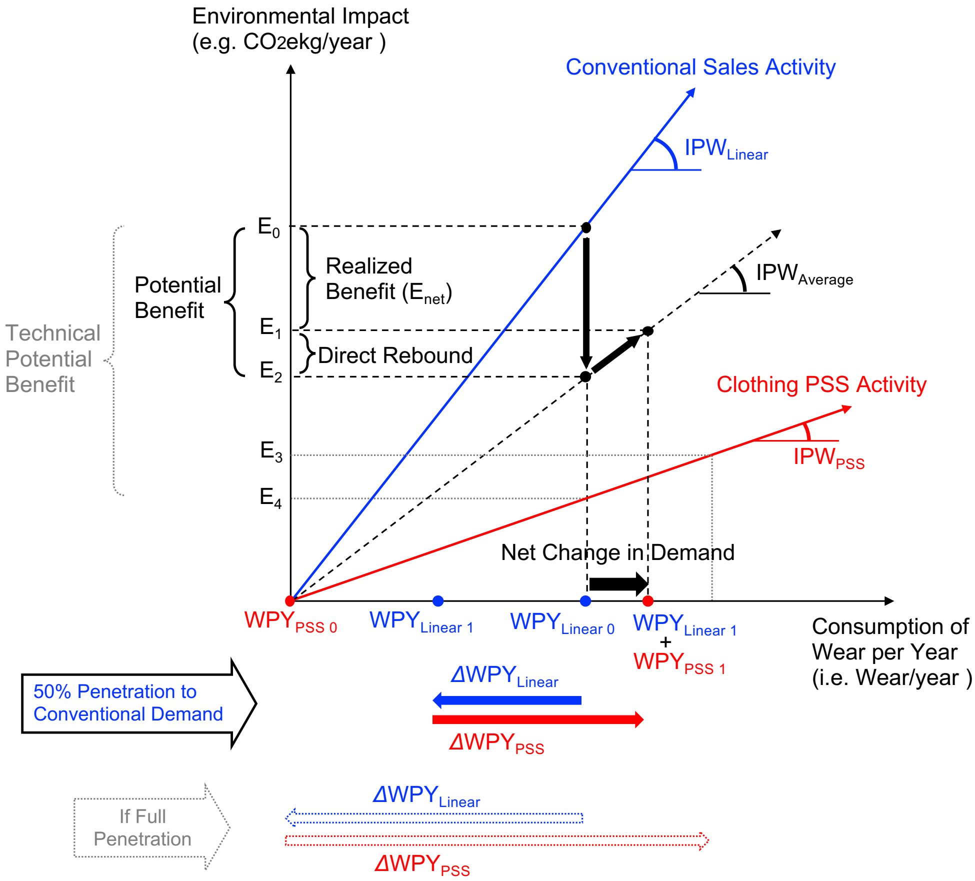

Figure 2 Use-PSS rebound attributed to introduction of Use-PSS for clothing [2]

If no rebound occurs, the potential benefit (constrained by a "penetration rate" (Wood et al., 2018:542)) can be realized and environmental impact falls from E_0 to E_2. However, if an increase in WPY_{PSS} is greater than a decrease in WPY_{Linear} (i.e. replacement rate of wear[3]*< 1), the net increase in consumption of wear reduces the net benefit by $E_1 - E_2$. Also, if one wear of Use-PSS clothing substitutes for one wear of linear clothing but does not fully reduce their purchase amount (i.e. effective replacement rate of wear < 1), it will offset the benefit.*[4]

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[2] Adapted from Zink & Geyer (2017:598) and modified by the author by replacing "e_r, e_p, ΔQ_r, ΔQ_p and Production (# units)" with "IPW_{PSS}, IPW_{Linear}, ΔWPY_{PSS}, ΔWPY_{Linear} and Consumption of Wear per Year (i.e. Wear/year)," respectively, and reflecting the concept of "penetration rate" (Wood et al., 2018:542) where only a fraction of conventional demand can realistically be subject to replacement by an innovation.

[3] For simplicity, the replacement rate of wear in ***Figure 2*** is assumed to be constant at 0.8 also under the case of full penetration, however, it might change dynamically according to different levels of market share.

[4] Impact per Wear (IPW) = Life cycle impact per garment / Actual number of times a garment is worn (including trial). If the introduction of use-PSS for clothing would ever reduce the utilization of conventional linear clothing, it will also offset the environmental benefit (i.e. the inclination of IPW_{Linear} and $IPW_{Average}$ in ***Figure 2*** increases).

2.6 Consumption-As-Usual assumption for LCA

Traditional LCA assumes constant volume of demand by setting a fixed functional unit, by which they represent functional equivalence between the compared products and services under study (Girod et al., 2011). Because of this, typical LCA studies cannot factor in the change in demand induced by more cost-efficient products and services (i.e. rebound effects). In order to overcome this limitation, Girod, De Haan, & Scholz (2011:3) suggested a "consumption-as-usual approach" that allows to test the potential range of rebound effects, by assuming that consumers aim for utility maximization under constant budget constraint, as in alignment with classic microeconomic consumer theory. Girod et al. (2011:6) suggest several consumer preferences to model the re-spending of saved resources in accordance with direct ("more of the same") and indirect ("more of the other") rebound effects.

2.7 Definitions and scoping applied for this study

To answer the research question, I will delimit the scope of the rebound effects to the economic and direct one, applying the assumption where consumers would simply demand "more of the same" (Girod et al., 2011:6) as financially affordable, for the following reasons. First, "identifying rebound effects equals identifying constraints" (Kjaer et al., 2017:38) and the analysis of direct rebound can be used to draw implications regarding the outcome from change in "consumption factors" (Kjaer et al., 2018:670) (e.g. money, time, space and access, etc.). Strategies to mitigate direct rebound applies to indirect rebound and simulation results for direct rebound can be also interpreted as a conservative outcome of indirect rebound. Second, an increase in demand of wear (e.g. phantom wear) which has not gained attention in LCA, can be only captured through modeling direct rebound. Third, academic and public debates to enhance and emphasize the relative price advantage of use-PSS for clothing (Ecopreneur.eu, 2019; Elander et al., 2017; Park & Joyner Armstrong, 2019; Tao & Xu, 2020) underpin the relevance with economic rebound effects.

Also for clarity, I define the 'effective replacement rate of wear' as 'the extent to which one facilitation of wear of Use-PSS clothing replaces one wear of conventionally sold clothing without compromising their clothing utilization' and differentiate from the case where one wear of Use-PSS clothing substitutes one wear of linear clothing but does not contribute to reducing the purchase rate of these garments. However, for simplicity, I will leave out such cases in this study and use the term 'replacement rate of wear' for 'effective replacement rate of wear.'

Chapter 3. Methodology

Here, the research strategy and methodological choice for this study are explained, followed by the descriptions of the data collection process and the research ethics.

3.1 Research Strategy and Methodology Choice

This study aims to increase the understanding of the environmental potential of subscription-based Use-PSS of clothing when direct economic rebound effects are taken into account. In order to achieve this aim, I carry out this study as an explorative theoretical research. The research is designed as of explorative and theoretical nature because its purpose is to “look at new and fairly under-researched topics to describe matters and discover new things” (Denscombe, 2012:102) and to increase understanding based on existing knowledge (de Gooyert & Größler, 2019), under the context where the consideration of direct rebound effect and change in total consumption of wear has been absent in the existing LCA literature.

To answer the research question, I use system dynamics (SD) modeling as a “conceptual virtual laboratory” (de Gooyert, 2019:660) which enables challenging the conventional assumption of constant demand of wear by conceptually demonstrating a what-if analysis by computer simulations. This approach was chosen to generate insight by consistently integrating existing knowledge of quantitative LCA studies (Johnson & Plepys, 2021; Piontek et al., 2020; Roos et al., 2016; Sandin et al., 2019; Zamani et al., 2017), theoretical frameworks related to rebound effect (i.e. “consumption-as-usual” (Girod, De Haan, & Scholz, 2011:3) and “circular economy rebound” (Zink & Geyer, 2017:593)), and other qualitative knowledge regarding CFC including Use-PSS for clothing. A theoretical SD model can serve as a framework where existing scientific knowledge can be integrated with clarity and further experimented upon, using secondary data as inputs (de Gooyert & Größler, 2019). Since these inputs involve both qualitative and quantitative data, a mixed-method research strategy that combines both qualitative and quantitative approaches (Denscombe, 2012) was applied.

System dynamics (SD) is a methodology that enhances the learning of complex systems and dynamic behavior over time (Sterman, 2000). It involves both the qualitative and quantitative phases (Luna-Reyes & Andersen, 2003), with its core strength of analyzing a system by mapping out its causal relations, identifying feedback loops, and provide endogenous explanations for the behavior over time (de Gooyert, 2019). While SD is often used to provide practical contributions in the real world, it is also a versatile method that can be used to provide a theoretical contribution in research (de Gooyert, 2019; de Gooyert & Größler, 2019). One reason for the application of SD for this study is to analyze the environmental potential of Use-PSS for clothing which involves a dynamic development of awareness towards clothing PSS and "consumption feedback loop" (Girod et al., 2011:5) that determines the change in the market share depending on consumer behavior. Another reason is because it enables a 'logically consistent synthesis' of the knowledge. To answer the research questions, I apply the research strategy of "conceptual virtual laboratory" (de Gooyert, 2019:660) with the main intention of providing a theoretical contribution through synthesizing existing knowledge in such a way that it reaches a new level of internally and logically consistent understanding (Repenning, 2002) of the environmental potential of subscription-based Use-PSS of clothing when direct economic rebound effects are taken into account, which in turn allows to discover new insights and unexpected results through extensive simulations of what-if analysis that also cover the scenarios that have not been observed in practice yet (Lomi, Larsen, & Wezel, 2010).

In order to achieve this, first I conduct a narrative literature review to map out the key concepts and causal relationships relevant to the research question (c.f. ***Table 2***, Appendix 1), which then serves as an input for the causal loop diagram (CLD), which is a qualitative SD tool that helps represent key variables and causal relationships visually and identify feedback loops (Forrester, 1992). Conceptualizing a CLD also serves as an aid for the formulation of a quantitative model (Spector, Christensen, Sioutine, & McCormack, 2001). After this, a quantitative model, as well as scenarios, were developed to conduct simulations that allow rigorous testing of hypothesis and virtual experiments of scenarios in a non-expensive and non-dangerous way (Sterman, 2000), which further enhanced coherent synthesis of the knowledge, while also providing "open boxes whose assumptions are fully known and can even be modified by the learner" (Sterman, 2000:35).

To run the simulations, scenarios were built to test hypothetical policies and derive implications of the relative potential of Use-PSS for dresses, while taking rebound effects into account. A base case scenario was built to represent a problematic state under the conventional business model, and reference policy as a case of switching material from virgin polyester to recycled polyester. Then scenarios applying Use-PSS of dress are demonstrated under various assumptions of consumer behavior and membership settings of PSS platforms. Finally, insights are drawn by contrasting existing knowledge in the literature with the results from simulation runs that the model internally generated (de Gooyert, 2019).

3.2 Data Collection and Analysis

Data and causal relationships related to the topic of PSS, LCA of clothing, consumer behavior, rebound effects, and microeconomics were collected through a narrative literature review. The literature search was carried out between March 2020 and February 2021 by searching the databases of Radboud University Library Repository and Google Scholar, to identify literature related to the topic of Product Service Systems (PSS), Life Cycle Assessment (LCA), Collaborative Fashion Consumption (CFC), consumer behavior related to clothing, and rebound effect, aiming at obtaining a broad overview of the leading scientific thoughts in academia. In addition, documents published by research institutes such as WRAP, Ellen Macarthur Foundation, Mistra Future Fashion, and European Commission were included as they provided additional qualitative and quantitative data, which enhanced rich understanding of the background of the research topic as well as served as inputs for the quantified model. The selection of literature and documents was done by 1) searching with keywords related to the above-mentioned topics, 2) snowball sampling of the references, and 3)screening by the relevance to the above-mentioned topics with the aim of answering the research question. Literature and documents which purely focused on fashion or circular business models without any considerations of clothing, PSS or LCA, were excluded.

3.3 Research Ethics

The study was conducted in accordance with the Ethical Principles of Psychologists and Code of Conduct (American Psychology Association, 2017). This research is entirely based on publicly available academic literature and institutional reports as listed in the references. Literature and documents are found through search engines as well as browsing relevant documents via snowball search and they are open to scientific use. This study will be stored in the Radboud Repository with accessibility to scientific researchers as well as the public who have access to the repository. The software used to model the CLD and quantitative SD model was Stella Architect software, version 2.0.3. None of the methods applied in this research will present any harm to any stakeholders.

Chapter 4. Results Ⅰ: Qualitative Analysis

4.1 Qualitative Analysis via Causal Loop Diagram

From the literature review, I developed the following CLD to conduct a qualitative analysis. Here, the CLD is explained by loop by loop in order to serve as an overview of the model. Key causal relationships identified in the literature are presented in ***Table 2*** in Appendix 1 and will be presented individually below.

4.1.1 Consumption of dress and annual carbon footprint

4.1.1.1 Linear (i.e. conventionally sold) dress

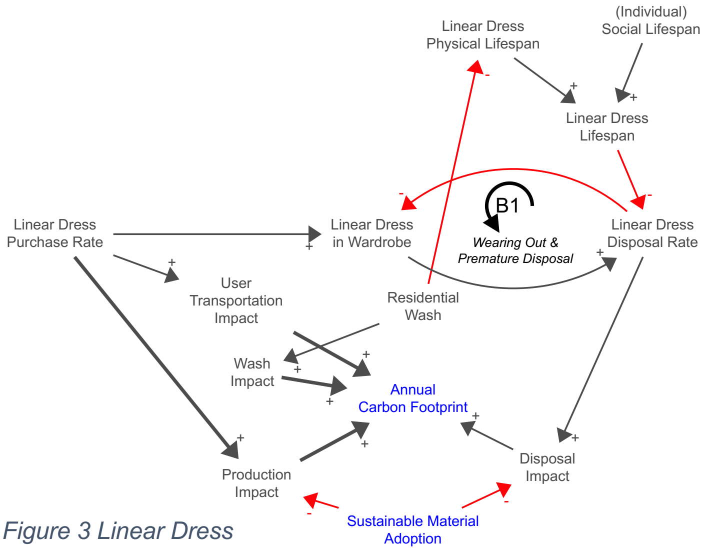


Figure 3 Linear Dress

Every purchased garment will be disposed of (Loop B1) either by being worn out or prematurely. The physical wear and tear of a garment occurs mainly in the washing cycle (Petersen & Riisberg, 2017) and a dress can be estimated to be washed every three times of wear on average (Sandin et al., 2019). The average lifespan of clothing is determined by the shorter of the physical lifespan (i.e. the duration a garment can withstand physical wear and tear) and the social lifespan (i.e. the duration considered to be socially acceptable to wear for the user) (Klepp, Laitala, & Wiedemann, 2020). Currently, because the social lifespan of a dress (i.e. 3.6 years) for individual users (WRAP, 2017) is shorter than its physical lifespan (e.g. 5 years), resulting in a high premature disposal rate (Iran & Schrader, 2017; Johnson & Plepys, 2021). The annual carbon footprint (CO_2ekg/year) is caused throughout the full life cycle of clothing and categorized into four main lifecycle stages, which are the impact of production, user transportation, wash cycles, and disposal. As for the linear model, the production impact accounts for more than 80% of the impact, whereas in the PSS model, the user transport impact accounts for nearly half of the impact if extendedly used by multiple users (Zamani et al., 2017). Switching from virgin polyester to chemically polyester or Tencel could reduce the annual carbon footprint by 6% (Sandin et al., 2019) or more than 6% (Shen, Worrell, & Patel, 2012), respectively.

4.1.1.2 PSS dress (rental/lease dress through monthly subscription)

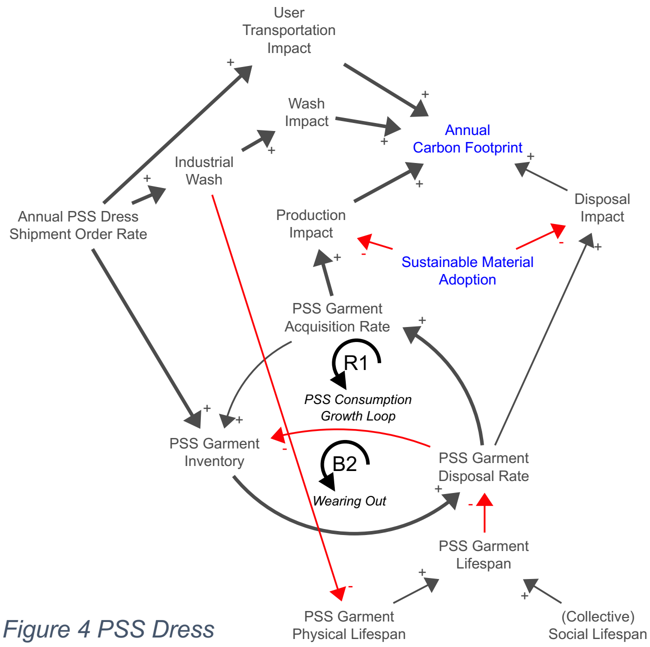


Figure 4 PSS Dress

Use-PSS seeks to collectively extend the active lifespan by sharing among multiple users so that a garment can be used until physically worn out at best (Loop B2). Inventory will be built up along with the growth of shipment order rate (Loop R1). However, the lifespan of Use-PSS products might be compromised if the users would use carelessly because they don't own them (Tukker, 2015), or if the increased speed of fashion could shorten the social lifespan of clothing even at a collective level, as some platforms frequently update the inventory to pick from the latest collections (Borg, Mont, & Schoonover, 2020). Besides the risk of increased transport by frequent transactions, Iran & Schrader (2017) and Zamani et al. (2017) referred to the risk of increased wash cycles. While an owned dress would normally be washed once in three times of wear (Sandin et al., 2019), a rental platform must rigorously clean it every time of rental in order to ensure that items are 'good as new' (Iran & Schrader, 2017). Although PSS platforms usually apply different cleaning process and not every garment will be fully dry-cleaned every time (Bertoni, 2014), this poses a challenge for preventing the physical lifespan from being compromised, because hygiene, perceived contamination, and odor are critical factors for user trust and satisfaction (Borg et al., 2020; Clube & Tennant, 2020). Also, while an industrial cleaning cycle could be more efficient than a residential cleaning cycle, customers could wash before and after the use of rental clothes at will (Zamani et al., 2017).

Moreover, every returned garment must be cleaned even if it was barely worn (i.e. phantom wear), potentially shortening the physical lifespan. For example, Rent The Runway provides a popular service where it offers a backup dress of different sizes for each rental in order to solve the fitting issue, which is normally difficult for a formal dress without an opportunity to try at the physical store (McKinney & Shin, 2016). Also, in fashion SOS, frequent mismatches between the users' expectation and actual product quality, fit, and selection is one of the key dissatisfaction factors for users (Niehm, 2020), which implies that many items are sent back without being utilized for actual wear occasions.

4.1.2 Market share and demand of wearing dresses

4.1.2.1 PSS dress market share

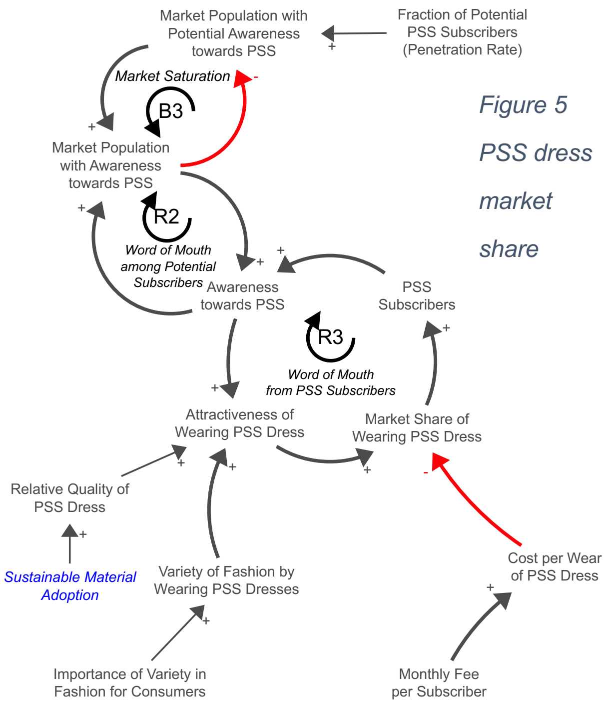


Figure 5 PSS dress market share

Key factors relevant to the adoption of Use-PSS of clothing is that it requires awareness and allows access to a wider variety and higher quality garments at a fraction of cost (Armstrong et al., 2016; Park & Joyner Armstrong, 2019). Since fashion rental is a radically novel model requiring ownership-less consumption, it entails a process of innovation diffusion (Tao & Xu, 2020) that needs substantial consumer awareness, which is both the critical barrier and enabler of this business model (Becker-Leifhold & Iran, 2018; Elander et al., 2017). Preference for ownership and consumption habit is difficult to be changed (Armstrong et al., 2015; Tukker & Tischner, 2006) and it takes time for clothing PSS to diffuse in the market. To begin with, there has to be enough fraction (i.e. penetration rate) of population for the garment type who might potentially consider Use-PSS and become subscribers. Consumers are generally not willing to attend PSS for next-to-skin products such as T-shirts and underwear because of hygiene concerns (Armstrong et al., 2015; Mukendi & Henninger, 2020). Awareness towards PSS in the model is captured as a general positive attitude towards using the fashion rental including hedonic (e.g. fun in shopping and experiment with a variety of styles), utilitarian (i.e. opportunities to save money, wear high-quality clothes that would have been not affordable) and bio-spheric (e.g. sustainability concern, frugality) motives (Becker-Leifhold & Iran, 2018). Subjective norms and word of mouth are highly influential for adopting fashion renting (Loop R2) especially from those who have previous rental experience (Loop R3) (Lee & Chow, 2020).

Within the pool of potential PSS subscribers in the market, market share is determined by the attractiveness of wearing PSS relative to its cost per wear (i.e. weighted attractiveness). One of the important attractiveness of clothing PSS is the amount of access to clothes and flexibility to swap the item (Becker-Leifhold & Iran, 2018) which allows users to fulfill the desire for novelty, variety, and change (Ellen MacArthur Foundation, 2017) while providing opportunities to try and experiment with styles (Mukendi & Henninger, 2020; Pedersen &

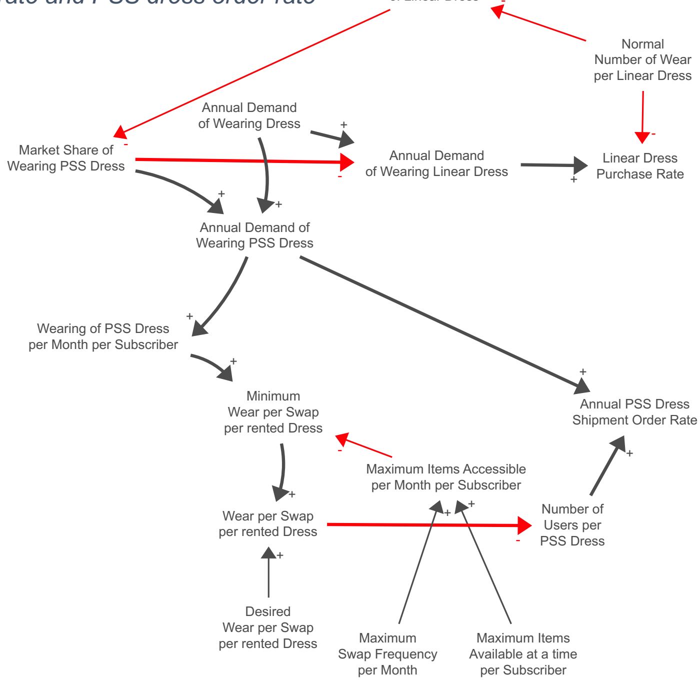
Netter, 2015). The importance of fashion variety depends on consumer types, where those who are more highly fashion-sensitive and eager to change styles have a higher incentive to use PSS (Johnson & Plepys, 2021; Shrivastava et al., 2021).

Another attractiveness for PSS users is that it can offer access to high-quality garments that would otherwise have been not affordable (Armstrong et al., 2016). Especially for high-end garments like formal dress, aesthetical quality (Becker-Leifhold & Iran, 2018; Mukendi & Henninger, 2020) and quality of the fabric (McKinney & Shin, 2016) are relevant. From this perspective, high quality but also sustainable material such as Tencel could positively affect the quality of the dress, as Tencel has an excellent technical durability and functionality along with silky touch compared to cotton (Basit, Latif, Baig, & Afzal, 2018; Good on You, 2020; Karthikeyan, Nalankilli, Shanmugasundaram, & Prakash, 2016).

Finally, the value for money is the critical driver for all consumers when choosing clothing (WRAP, 2012) and as well as for clothing PSS (Park & Joyner Armstrong, 2019). If prices are the same, consumers prefer to choose conventional consumption that allows ownership (Armstrong et al., 2016). The rental or leasing model consists of users paying a subscription fee, in exchange for access to a large inventory of clothes that are shared among the users (Kjaer, Pigosso, Niero, et al., 2018). Cost per wear is the average cost corresponding to facilitated wear through fashion rental.

4.1.2.2 Linear dress purchase rate and PSS dress order rate

Figure 6 Linear dress purchase rate and PSS dress order rate



The annual purchase rate of linear dress and shipment order rate of PSS dress originates from the annual demand of wearing of dress per year split by the market share. In the model, the cost per wear of linear dress is treated as a constant reference value resulting from the average retail price and the normal number of wears for a linear dress, assuming a large and stable demand of linear dress in the entire market a consumer has access to. As for PSS, an important determinant of shipping order rate is the number of users per PSS dress's life cycle, which is further determined by the number of times a rented dress is worn per user (i.e. Wear per Swap, WPS)(Zamani et al., 2017). The fewer the users per garment, the fewer the shipping needs and transportation impact. Thus, as long as one rental can facilitate multiple times of wear per user, the potential environmental benefit will be significantly higher (Johnson & Plepys, 2021).

The actual WPS is determined by the desired WPS by a subscriber as long as it is above the minimum. The minimum WPS represents the availability constraint of variations in PSS dress as it is determined by the demand (i.e. monthly consumption of wear (including trial) of PSS dress per subscriber) divided by the number of maximum items accessible per month for each subscriber, which typically consists of a maximum items available at a time and a maximum opportunity of swap per month (Gilliot, 2019; Tu & Hu, 2018). For example, if a subscriber wants to wear a dress 16 times in a month but only has maximum access to eight PSS dresses per month (e.g. maximum of four items at a time * maximum of two swaps per month), then each PSS dress has to be worn at least twice (i.e. minimum WPS = 2) to cover the demand, even though if the subscriber originally wanted to "Never wear the same thing twice"(Joyner Armstrong & Park, 2017:11) (i.e. desired WPS =1).

4.1.2.3 Demand per subscriber, variety availability constraint, and charge for swap frequency

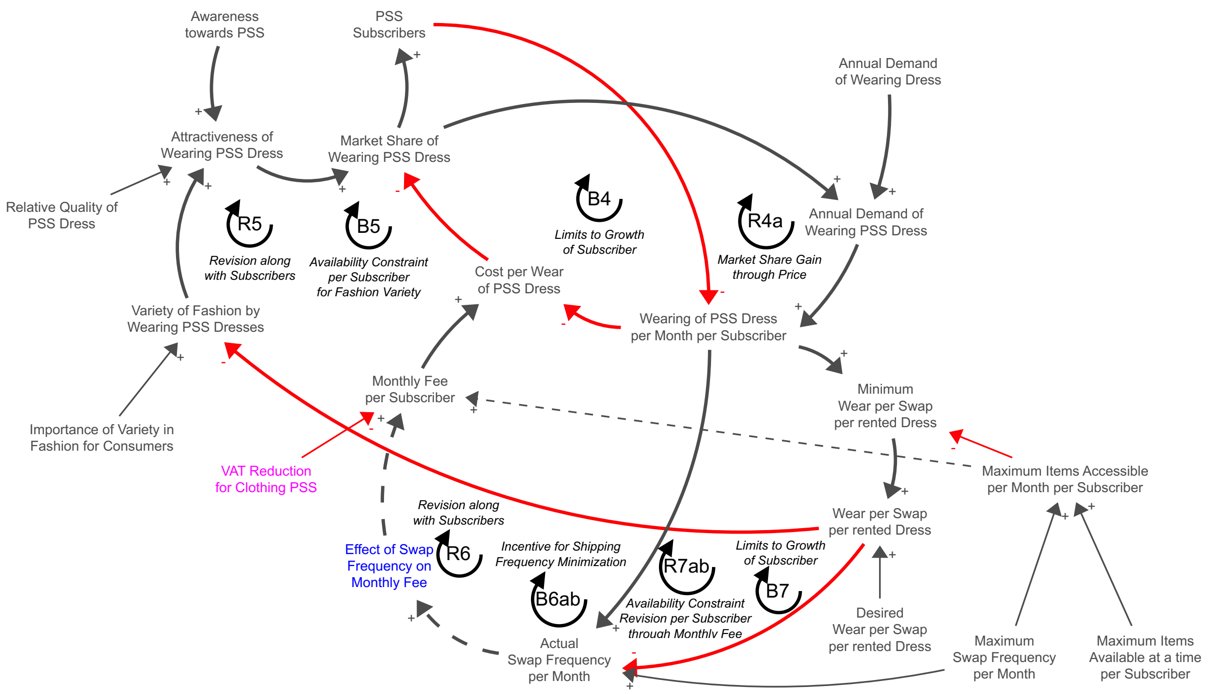


Figure 7 Demand per subscriber, variety availability constraint, and charge for swap frequency

In the fashion rental subscription model (i.e. leasing based on flat monthly fee), the cost per wear of PSS dress is a monthly fee divided by the amount of wear per month per subscriber. The setting of the monthly fee depends on PSS platforms, however, in general, each platform offer several flat monthly fee based on a maximum items available at a time, and a maximum swap frequency per month (i.e. once, twice, four times or even unlimited swaps per month where the only constraint will be the shipping time required for each swap) (Gilliot, 2019; Tu & Hu, 2018).

PSS demand growth loop (B4 and R4a):

An increase in demand for wearing PSS dresses consists both of an increase in demand per subscriber and the increase in the number of subscribers. By definition, the cost per wear of PSS dress decreases as one subscriber consumes more wear (including trial) of PSS dress in a month, under a given flat monthly fee. Within the limitations of maximum items available per month, subscribers are allowed to access as many items as possible by increasing the transaction frequency. By doing so, a subscriber can further benefit from increased variety of wear as well as reduced cost per wear (Pedersen & Netter, 2015) (Loop R4a). At the same time, cheaper cost per wear would also attract more PSS subscribers which will grow until a reduction in cost per wear no longer attract them (Loop B4). If the total annual demand for wearing dresses remained constant (i.e. if there is no Use-PSS rebound), a reduction in cost per wear of PSS dress leads to a pure substitution for the demand for wearing linear dresses (i.e. replacement rate of wear = 1). A reduction in monthly fees through the effort of PSS platforms or VAT reduction could thus increase the substitution for linear dress under this condition.

Variety availability loop (B5 and R5):

Lower actual WPS means each time of wear occasion can be satisfied with higher variety and novelty of PSS dresses, which also provides more opportunities to try and experiment with styles (Mukendi & Henninger, 2020; Pedersen & Netter, 2015). This is particularly attractive for those who have high fashion consciousness (Lee & Huang, 2020; Shrivastava et al., 2021) which drives the market share of wearing PSS dress. However, if the maximum number of items accessible per month is low enough, an increase in demand of wear per subscriber could push the minimum WPS above the desired WPS (e.g. as in the example on p.29) where the subscriber has to compromise with an increased WPS to cover the demand (Zamani et al., 2017), which will decrease the attractiveness of fashion variety, especially when the subscribers have high fashion consciousness. This will put a limitation on the attractiveness of PSS dress and thus on the demand of wear per subscriber (Loop B5) while the restriction grows along with the number of subscribers (Loop R5).

Transaction minimization loop (B6a and R6):

The more a subscriber demands wearing (including trial) of PSS dress in a month and the fewer the desired WPS, the more frequently the items have to be exchanged within the limitation of maximum swaps allowed per month. Zamani et al. (2017) proposed linking the transaction frequency to users' monthly fees in order to incentivize minimizing their transaction. If in effect, this will increase the monthly fee and thus the cost per wear of PSS, constraining the swap-driven growth in demand per subscriber (Loop B6a) while the constraint grows along with the number of subscribers (Loop R6).

Variety availability constraint loop (R7a and B7):

If the monthly fee is linked with the transaction frequency (Loop B6a), the effect of change in minimum WPS could be amplified in the range where minimum WPS is higher than desired WPS. Lower WPS increases swap frequency and thus the monthly fee and cost per wear, which reduces the demand per subscriber, further lowering the minimum WPS and relaxing the variety availability constraint (i.e. even lower desired WPS is possible) (Loop R7a). Or the contrary, higher WPS reduces swap frequency and thus the monthly fee and cost per wear, which increases the demand per subscriber, further increasing the minimum WPS and thus the actual WPS (i.e. if minimum WPS > desired WPS) (Loop R7a). Higher/cheaper cost per wear repels/attracts more PSS subscribers which will decrease/grow until an increase/reduction in cost per wear no longer repels/attracts them (Loop B7).

4.1.2.4 Direct economic rebound effect

The diagram below represents the economic rebound effect where consumers would increase fashion consumption as long as affordable (i.e. "consumption-as-usual" (Girod et al., 2011:3)) (Loop B8) depicting their utility maximization (UM) behavior. In such a case, the demand for wearing a dress per person increases until the same level of expenditure, which will further drive the cost per wear of PSS downwards, activating the hyper-

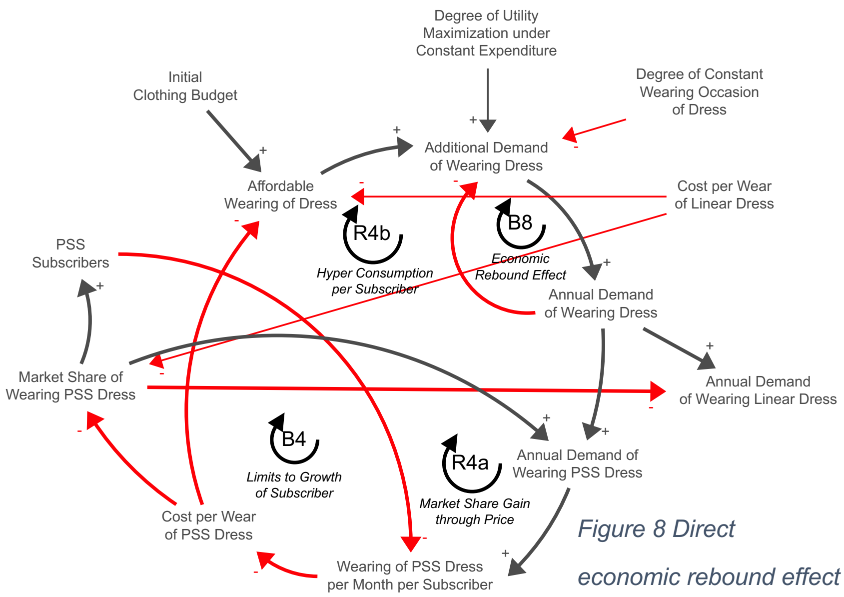


Figure 8 Direct economic rebound effect

consumption loop (Loop R4b). Unlike the individually priced pay-per-use model, a monthly fee based on a flat rate with free shipping holds an implicit incentive to maximize the items available per month (Pedersen & Netter, 2015).

While the same phenomena can occur when linear clothing gets cheaper, for the purpose of the model to investigate the relative potential of PSS compared to the conventional retail model, retail price and normal wear per linear dress is fixed at constant, making the cost per wear of the linear dress constant as well. The behavior leading to economic rebound depends highly on the degree of consumers to pursue additional spending on wear for maximizing utility or will be satisfied when fulfilled the needs of wear for a constant wear occasion. While they could re-spend the money also by spending on other products and services (e.g. other types of clothes or other consumption in general), in this model, it focuses on the direct rebound which means the consumers are assumed to spend on additional wear of dress.

4.2 Formulation of Simulation Model and Model Boundary

Based on the key causal structure identified in the CLD, a computational model was developed in order to enable simulation. The overview of CLD, the model boundary chart, and the overview of the quantitative model and its documentation are presented in Appendix 2, 3, 4, and 7, respectively. The model is checked with its dimensional consistency as it emits no error in the simulator. The software used to model the CLD and quantitative SD model was Stella Architect software, version 2.0.3. The specifications for simulation were: 1) Time unit: year, 2) Time step (DT): 0.01, 3) Time horizon: 2020-2030, and 4) Integration Method: Runge-Kutta 4.

4.3 Major Assumptions applied to Simulation Model

4.3.1 Current state of the consumption in market A

Most fundamentally, the current state is represented as the case where an average person who buys dresses purchase 5 dresses per year and wear it for 10 times (Roos et al., 2015), with the social lifespan of 3 years for dress for daily wear (c.f. 3.6 years for dresses including formal dress (WRAP, 2017).

4.3.1.1 Fraction of potential subscribers (i.e. potential penetration rate)

It is hypothesized that only a certain fraction in the market is ever willing to consider adopting clothing PSS for fulfilling the needs of wearing dress, regardless of the relative cost advantage or attractiveness of PSS dress. For the fraction of 'never adopters,' the ownership-less consumption is simply not an option since they prefer purchasing or don't have any needs to change the styles frequently. In order to factor in this fraction, the concept of penetration rate (Wood et al., 2018) is used as a value that exogenously determines the potential pool of PSS subscribers, where an exogenous value of 0.5 is used.

4.3.2 Formulation of market share and demand of wear

Since this study aims to investigate the carbon footprint reduction potential of Use-PSS for clothing while taking the economic rebound effect into account, the annual demand of wear was modeled as an endogenous variable as the affordable amount of wear (including trial). This is assuming UM behavior under constant expenditure, in alignment with microeconomic consumer theory and the "consumption-as-usual" concept for LCA (Girod et al., 2011:3).

4.3.2.1 Principle for share of demand

Formulation of Market share of wearing of PSS dress is modeled as a share of attractiveness of wearing PSS dress weighted by its cost per wear. Such formulation is in alignment with a survey result in a UK study that indicated the most important criteria for consumers when choosing clothing is "value for money" (WRAP, 2014:4). Formulation of market share can be modeled as an outcome of the share of the attractiveness of the product (Sterman, 2000) while the attractiveness (before factoring in price) of products are weighted with their respective prices.

Putting α and β as the Attractiveness of wearing a PSS dress and the Attractiveness of wearing a linear dress, respectively,

$$Weighted\ Attractiveness\ of\ wearing\ a\ PSS\ dress = \frac{\alpha}{CPW_{PSS}}$$

$$Weighted\ Attractiveness\ of\ wearing\ a\ Linear\ dress = \frac{\beta}{CPW_{Linear}}$$

$$\begin{aligned} &Market\ share\ of\ wearing\ a\ PSS\ dress \\ &\quad = \frac{Weighted\ Attractiveness\ of\ wearing\ a\ PSS\ dress}{Total\ Weighted\ Attractiveness\ of\ wearing\ a\ dress} \\ &\quad = \frac{\frac{\alpha}{CPW_{PSS}}}{\frac{\alpha}{CPW_{PSS}} + \frac{\beta}{CPW_{Linear}}} \end{aligned} \tag{3}$$

4.3.2.2 Behavior of Utility Maximization (UM)

In alignment with classic microeconomic theory and the formulation of market share above, in order to model the change in demand induced by relative cost per wear of Use-PSS, this study models consumers' preference by applying a Cobb-Douglas Utility function (Besanko & Braeutigam, 2020; Yin, 2001).

Utility achieved by wearing of PSS dress per year (WPY_{PSS}) and linear dress per year (WPY_{Linear}) = U (WPY_{PSS}, WPY_{Linear}):

$$U = WPY_{PSS}{}^{\alpha} * WPY_{Linear}{}^{\beta} \tag{4}$$

where α is the attractiveness of wearing a PSS dress and β is that of wearing a linear dress.

In order to model the utility maximization problem under certain budgetary limits, each consumer is assumed to follow the following budget constraint formula:

Annual Clothing Budget (B) = Annual Expenditure for PSS Dress + Annual Expenditure for linear Dress = Wear per Year of PSS dress (WPY_{PSS}) * Cost per Wear of PSS dress (CPW_{PSS}) + Wear per Year of linear dress (WPY_{Linear}) * Cost per Wear of linear dress (CPW_{Linear}), that is,

$$B = WPY_{PSS} * CPW_{PSS} + WPY_{Linear} * CPW_{Linear} \tag{5}$$

When the utility function is formulated as a Cobb-Douglas Utility function such as formula (4), it is known that solving the above equation is essentially the same as dividing the expenditure according to the share of the attractiveness of each option (Besanko & Braeutigam, 2020; Yin, 2001). Hence, utility maximization under a budget constraint can be achieved when the budget is shared according to the proportion of attractiveness of wearing PSS dress and linear dress as,

$$Budget\ for\ PSS\ dress\ (B_{PSS}) : Budget\ for\ linear\ dress\ (B_{Linear}) = \alpha : \beta$$

which further determines each budget for wearing PSS and linear dress as:

$$B_{PSS} = B * \frac{\alpha}{\alpha + \beta} \quad and \quad B_{Linear} = B * \frac{\beta}{\alpha + \beta} \tag{6}$$

4.3.3 Attractiveness of wearing PSS dress

The attractiveness of wearing a PSS Dress is defined as:

Attractiveness of Wearing PSS Dress (α) = Reference Attractiveness of Wearing Dress * Effect of Awareness on PSS Attractiveness * Effect of Fashion Variety on PSS Attractiveness * Effect of Relative Quality of Dress on PSS Attractiveness (7)

The Reference Attractiveness of Wearing Dress depicts the basic attractiveness of wearing a dress including fashion-ability, quality, and other factors, which are the same as linear dress. The Effect of Awareness on PSS Attractiveness captures the degree that awareness plays a role in PSS attractiveness, including consumption habits, sustainability concerns, and hedonic and utilitarian values. The Effect of Fashion Variety on PSS Attractiveness captures the value in PSS that it enables to change the style and size and fit as frequently as possible, where one varied wear of PSS dress would have a different value than one repeated wear of a linear dress. Effect of Relative Quality is only factored in to demonstrate the case of adopting high-quality sustainable material for PSS dress, although otherwise, the effect has no effect on attractiveness.

4.3.4 Consumer behavior

4.3.4.1 Constant Wear (CW) and Utility Maximization (UM) scenario

Two cases of consumer behavior; the Constant Wear (CW) scenario and Utility Maximization (UM) scenario are considered. The former represents a situation where the total annual consumption of wear stays constant, while the latter relaxes that assumption and assumes that consumers would maximize consumption as long as affordable. The gap between the annual carbon footprint of CW and UM scenarios represents the potential range of Use-PSS rebound.

4.3.4.2 Desired wear per dress per swap (Desired WPS)

It is assumed that the consumers have their desired number of wear per dress in each time of swapping, in order to wear different styles each time. As long as available, they can maximize the variation of dresses to wear. If the WPS is low, this will result in a higher number of customers and thus the shipment rate, resulting in a higher carbon footprint per PSS dress.

4.3.4.3 Importance of variety in wearing dresses for consumers

Consumers' average importance on variety in wearing dresses is represented as variance in average fashion consciousness of low (0.2), middle (0.5), and high (0.8).

4.4 Scenario Description

4.4.1 Reference demand (Run 1)

The default demand for wearing a dress is assumed to be 50 times a year based on (Roos et al., 2015). This is relatively a large amount of volume, compared to occasion formal wear. The occasion of wearing is assumed to be concentrated in 4 months (e.g. summer) and the monthly fee for PSS dress only applies to subscribers and subscription month. The reference garments are casual dresses available at conventional retail, and a low-mid price range is assumed (60EUR/dress) to represent the current major consumption of dresses affected by fast fashion.

4.4.2 Reference policy scenario under conventional linear business model (Run 2)

The reference policy is represented as a case where all the dress is instantaneously switched to made from chemically recycled polyester (i.e. with both penetration rate and replacement rate of 100%), yielding a 6% reduction in annual carbon footprint (Roos et al., 2016). This is for simplicity to serve as a reference upon which the scenarios with Use-PSS can be compared, while in reality the penetration rate might be lower and the change in material also takes time.

4.4.3 Scenario introducing PSS dress into Market A (Run 3 to 20)

As for the initial state of Market A, it is assumed that 5% of the total population has awareness towards PSS (i.e. a potential penetration rate of 0.5 and within that pool, an initial share of population with awareness towards PSS of 0.1). From there, the market share of Use-PSS for clothing is assumed to develop over time because of the growth in awareness and change in cost per wear and relative fashion variety of PSS dress. Various scenarios are explored by varying consumer behavior described in ***subchapter 4.3.4*** as well as membership design of platforms regarding maximum items accessible and swaps per month, and charge on swaps.

4.4.4 Scenario parameters

Key control variables are displayed as follows, while the full set can be seen in Appendix 5.

Key Control Variables		100% LINEAR		Introducing PSS Dress							
		Reference Scenario		Unlimited Swap & Flat Fee					Unlimited Swap & VFee		
	Scenario→	Run 1	Run 2 Lin-ear Policy	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	
	↓Control Variables	Base Run		CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	Unit
Consumer Variables	Average Fashion Consciousness	0.5	0.5	**0.2**	**0.8**	0.5	0.5	0.5	0.5	0.5	Unitless
Consumer Variables	Desired Number of Wear per Leased Dress per Swap (WPS)	1	1	1	1	1	2	3	1	3	wear /dress
Retailers/ Platform Variables	Maximum Items Available at a time per Subscriber	3	3	3	3	3	3	3	3	3	dress /person
Retailers/ Platform Variables	Max Swap Frequency per Subscription Month	6	6	6	6	6	6	6	6	6	1/month
Retailers/ Platform Variables	Reference Flat Monthly Fee per Subscriber	60	60	60	60	60	60	60	60	60	EUR/month/person
				FLAT RATE FEE regardless of swap frequency					Variable fee		
									c.f.Run5	c.f.Run7	

		Introducing PSS Dress											
		Limited Swap & VFee				VAT Reduction		Lifespan Degradation			+PSS Attractiveness		
	Scenario→	Run 10	Run 11	Run 12	Run 13 *	Run 14	Run 15	Run 16	Run 17	Run 18	Run 19	Run 20	
	↓Control Variables	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	Unit
Consumer Variables	Average Fashion Consciousness	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Unitless
Consumer Variables	Desired Number of Wear per Leased Dress per Swap (WPS)	1	3	1	1	1	1	1	2	3	1	1	wear /dress
Retailers/ Platform Variables	Maximum Items Available at a time per Subscriber	3	3	5	3	3	3	3	3	3	3	3	dress /person
Retailers/ Platform Variables	Max Swap Frequency per Subscription Month	2	2	2	2	6	2	6	6	6	2	2	1/month
Retailers/ Platform Variables	Reference Flat Monthly Fee per Subscriber	60	60	60	60	51	51	60	60	60	60	60	EUR/month /person
		Variable fee based on actual swaps				Flat	Variable	FLAT RATE FEE			Variable Fee		
		c.f.Run5	c.f.Run7	c.f.Run10	c.f.Run10	c.f.Run5	c.f.Run10	c.f.Run5	c.f.Run6	c.f.Run7	c.f.Run10	c.f.Run10	

*Initial Annual Wear Occasion of Dress per Person = 25 wear/year/person instead of 50 wear/year/person
Initial Linear Dress Purchase Rate per Person = 2.5 dress/year/person instead of 5 dress/year/person

Table 1 Key parameters for scenario runs

Chapter 5. Results Ⅱ: Simulation Analysis

Two cases of consumer behavior; Constant Wear (CW) and Utility Maximization (UM) scenario are separately shown after Run 3.

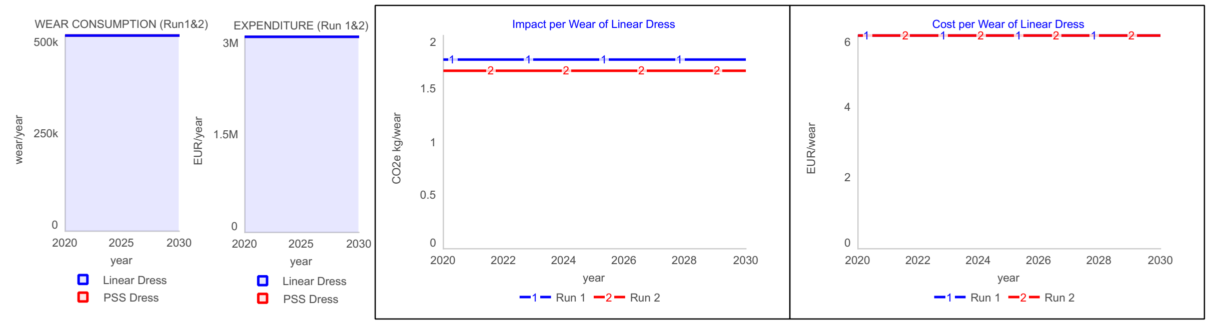


Figure 9 Base Run & Reference Policy under linear consumption

Run 1 (Base Run), Virgin Polyester, IPW_{Linear} = 1.77 CO2e kg/wear

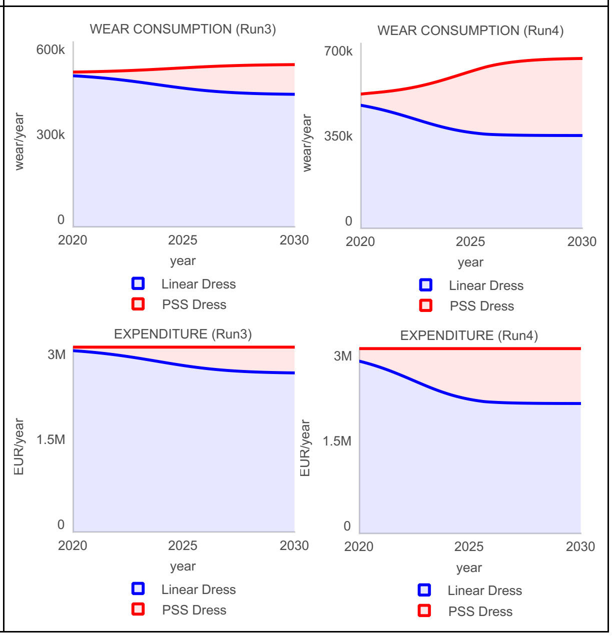
Run 2 (Linear Policy Run), Recycled Polyester, $IPW_{Linear\ Recycle\ PET}$ = 1.67 CO2e kg/wear

Run 1 and 2 serve as reference scenarios, representing the status quo and a policy available under the current linear business model. A person buys 5 new linear dresses per year and wears for 50 times a year. Assuming each dress costs 60 Euro, the reference cost per wear (i.e. CPW_{Linear}) is 6 EUR/wear.

5.1 Unlimited swaps under flat-rate monthly fee (free shipping)

Run 3 & 4, WPS = 1, IPW_{PSS} = 1.58 CO2e kg/wear → IPW_{PSS} / IPW_{Linear} = 89%

Run 3 and 4 represent the case where the average fashion consciousness of consumers is low or high, meaning the attractiveness of wearing Use-PSS clothing being low or high.

Constant Wear (CW) Scenario	Utility Maximization (UM) Scenario
	

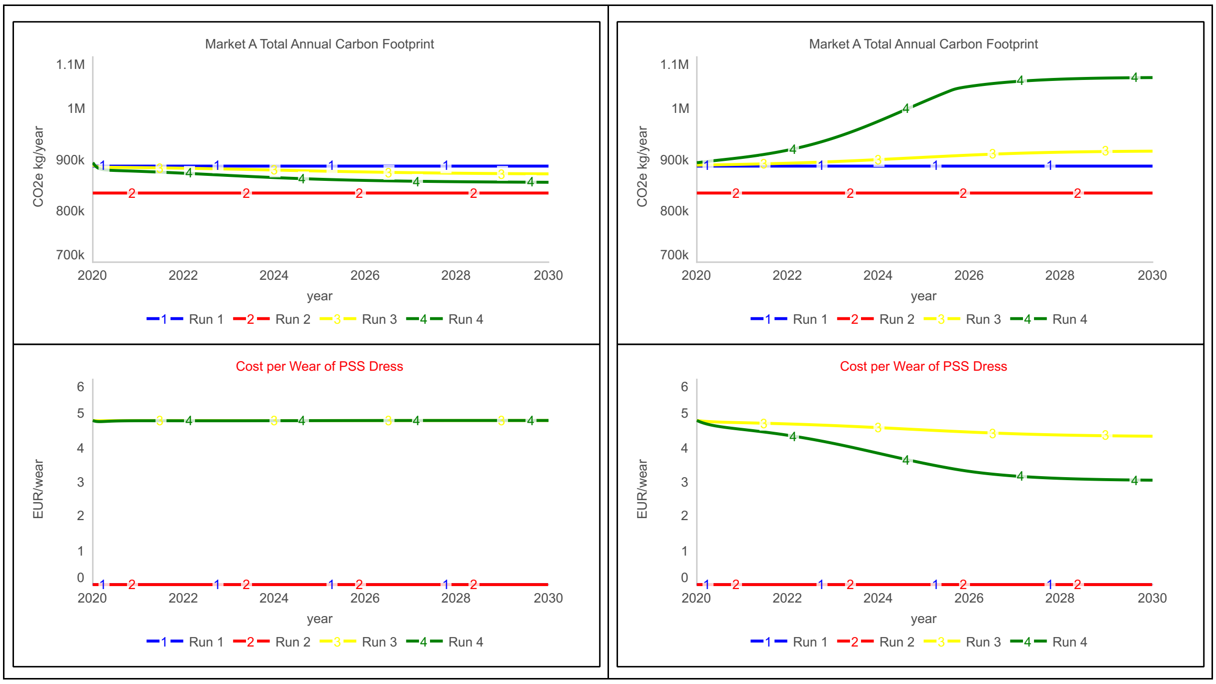


Figure 10 Unlimited swaps/Flat monthly fee: Change in Fashion Consciousness (Low & High)

Because of $IPW_{PSS} < IPW_{Linear}$, for CW scenario, higher attractiveness causes more pure substitution and thus carbon footprint saving (Run 4). However for UM scenario, because of $CPW_{PSS} < CPW_{Linear}$, consumers increase the consumption of wearing opportunity of PSS dress, causing a rebound. The higher the attractiveness of PSS, the more significant the rebound will be (Run 4). The gap between CW and UM in Run 3 and 4 depicts the potential range of Use-PSS rebound. Under unlimited swaps under flat-rate monthly fee with free shipping, users can increase consumption without additional cost and thus incentivized to do so by increasing the swap frequency, leading to a hyper-consumption (Loop R4b), unless they voluntarily cease consumption based on a fixed wear occasions as in CW.

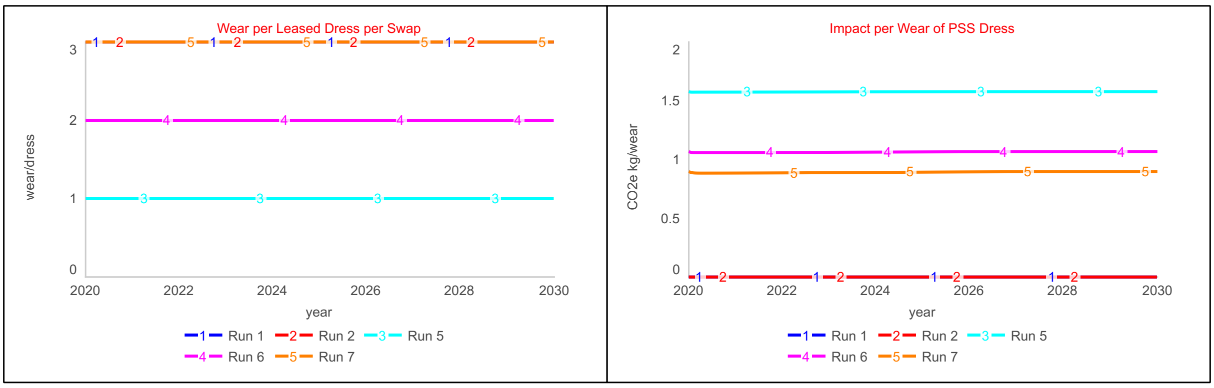


Figure 11 Effect of Wear per Swap on Impact per Wear

Run 5, WPS = 1, IPW_{PSS} = 1.58 CO2e kg/wear → IPW_{PSS} / IPW_{Linear} = 89%

Run 6, WPS = 1, IPW_{PSS} = 1.07 CO2e kg/wear → IPW_{PSS} / IPW_{Linear} = 61%

Run 7, WPS = 1, IPW_{PSS} = 0.89 CO2e kg/wear → IPW_{PSS} / IPW_{Linear} = 50%

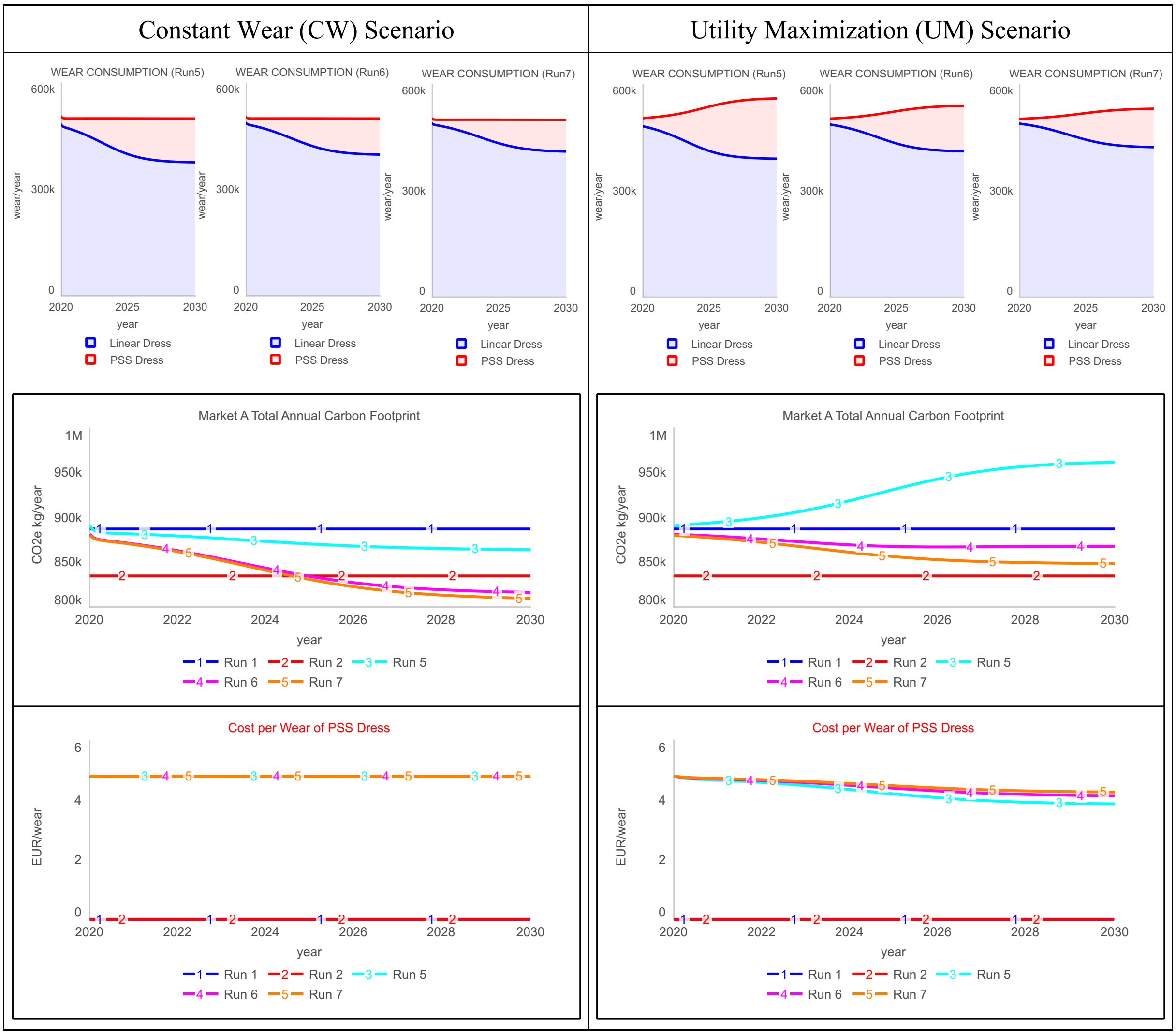


Figure 12 Unlimited swaps/Flat monthly fee: Change in WPS (1, 2, 3)

Meanwhile, an increase in WPS significantly reduces IPW_{PSS} as a higher number of wears per user means fewer users and transport needs per garment. Especially, the difference between WPS of 1 and 2 is the largest, significantly increasing the carbon footprint saving potential. Importantly, such a radical reduction in IPW_{PSS} makes the outcome of carbon footprint more robust against consumer behavior. The gap between CW and UM scenario is wide for Run 5, however it significantly reduces for Run 6. Nevertheless, lower WPS means more variety of PSS dress and thus increases attractiveness and market share, which under CW means more substitution and under UM more penetration but also rebound (Run 5). However, the reduction in IPW_{PSS} by an increase in WPS is far more effective to reduce the annual carbon footprint than an increase in substitution, highlighting the priority to increase the WPS (Run 6 &7).

An important remark is that this membership system of unlimited swaps under a flat-rate monthly fee is highly vulnerable to hyper-consumption and rebound, depending heavily on consumer behavior.

5.2 Limited swaps under variable monthly fee (charging for transaction)

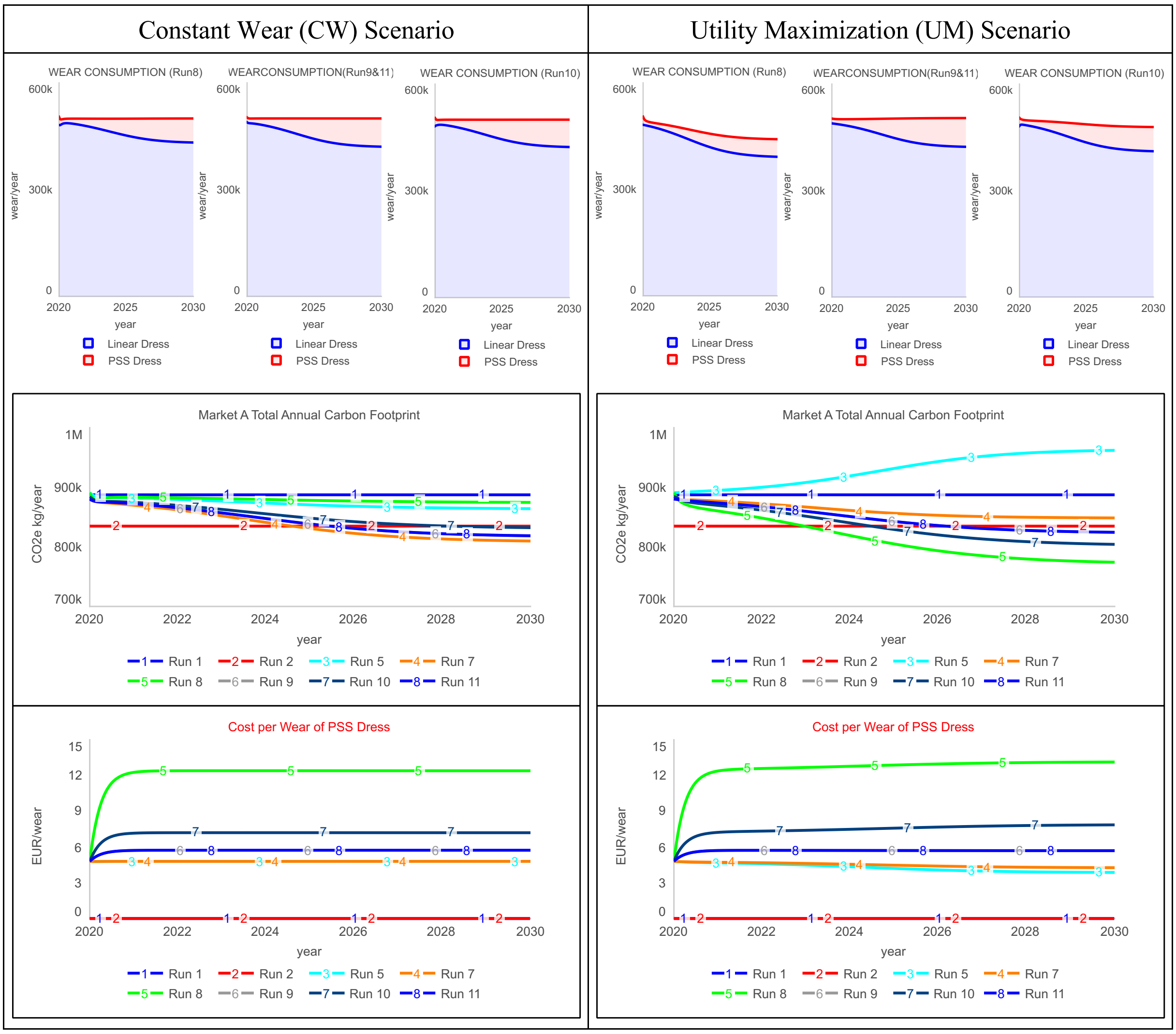


Figure 13 Unlimited to Limited swaps & Variable monthly fee: Change in WPS (1 & 3)

Run 5 and 7 corresponds to the runs shown in ***Figure 12***. Run 8 and 9 demonstrates the effect of introducing variable monthly fee based on actual swap frequency, under unlimited swaps. Focusing on the difference with previous runs, it is evident that the additional balancing feedback loop (Loop B6b) contributes to mitigate rebound risk under UM behavior (Run 8 & 9 compared to Run 5 & 7, respectively) because an increase in demand which will realize through an increase in swap frequency will be now accompanied by an increase in price, which puts a hold on hyper-consumption. However, as long as the maximum transactions are not technically limited, users could still use the clothing rental with WPS of one if they insist to (Run 8). Run 8 demonstrates such a hypothetical case where users would spend so much money on PSS so that they financially constrain their clothing demand under UM scenario, or spend significantly more than usual under CW scenario, which is rather an unrealistic case. However, this case underpins the possibility that the membership system would allow such consumption for some users who insist on the highest variety and still can afford it (Run 8 in CW scenario). Moreover, an important point is that even in such a case, there is not a meaningful carbon footprint reduction as long as the WPS is one, because of the high relative impact per wear of PSS dress (89%) that yields only negligible emission saving per substitution of wear. In order to eliminate such a chance and make it more robust against consumer behavior, Run 10 and 11 represent the case which delimits the max swap frequency technically, to twice per month.

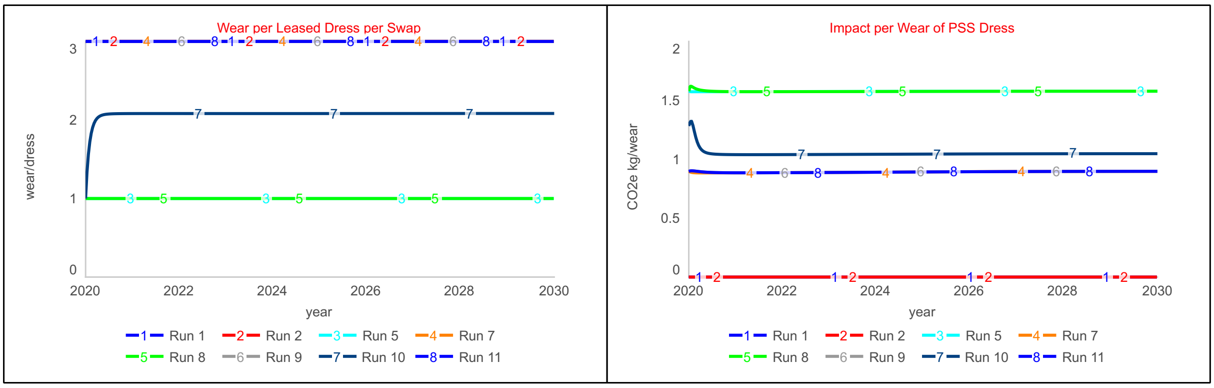


Figure 14 Limited max swaps & max item at hand raises WPS: Change in WPS (1 & 3)

By technically limiting the availability of dresses accessible per month (Loop R7ab), it induces the minimum WPS to increase above one wear to satisfy the monthly demand of wear, even if the users originally wanted to wear different dresses every time (Run 10 compared to Run 8). This reduces the IPW_{PSS} significantly and thus increases emission saving potential, closing the gap between the carbon footprint between CW and UM scenario (i.e. decreasing the impact range of Use-PSS rebound) (Run 10). At the same time, the max item at a time must be also small enough (e.g. three items at a time in Run 5,7,8,9,10 and 11) to increase the minimum WPS meaningfully, and if it is large (e.g. five items at a time in Run 12, Appendix 6), it would still allow WPS of close to one for a monthly demand of 12.5 wear/month /person. It also needs that the monthly demand is sufficiently large, since if the monthly demand is small (e.g. 6.25 wear/month/person in Run 13, Appendix 6), the minimum WPS stays lower than one and hence the actual WPS remains at the desired number of one wear.

An important remark, however, is that this membership system of limited swaps under variable monthly fee based on actual swap frequency is more robust against consumer behavior of CW or UM and thus potential hyper-consumption. At the same time, its limitations (Run 12 and 13, Appendix 6) are revealed, highlighting the importance of more proactive measures to promote a higher number of WPS (i.e. multiple wears per rented dress).

5.3 VAT reduction

A 15 % reduction in monthly fees due to a reduced VAT rate, which reduces the reference monthly fee from 60 to 51 EUR/month/person (Run 14 & 15), is tested for two memberships; the 'unlimited swaps under flat-rate monthly fee (free shipping)' (Run 5) and the 'limited swaps under variable monthly fee (charging for transaction)' (Run 10).

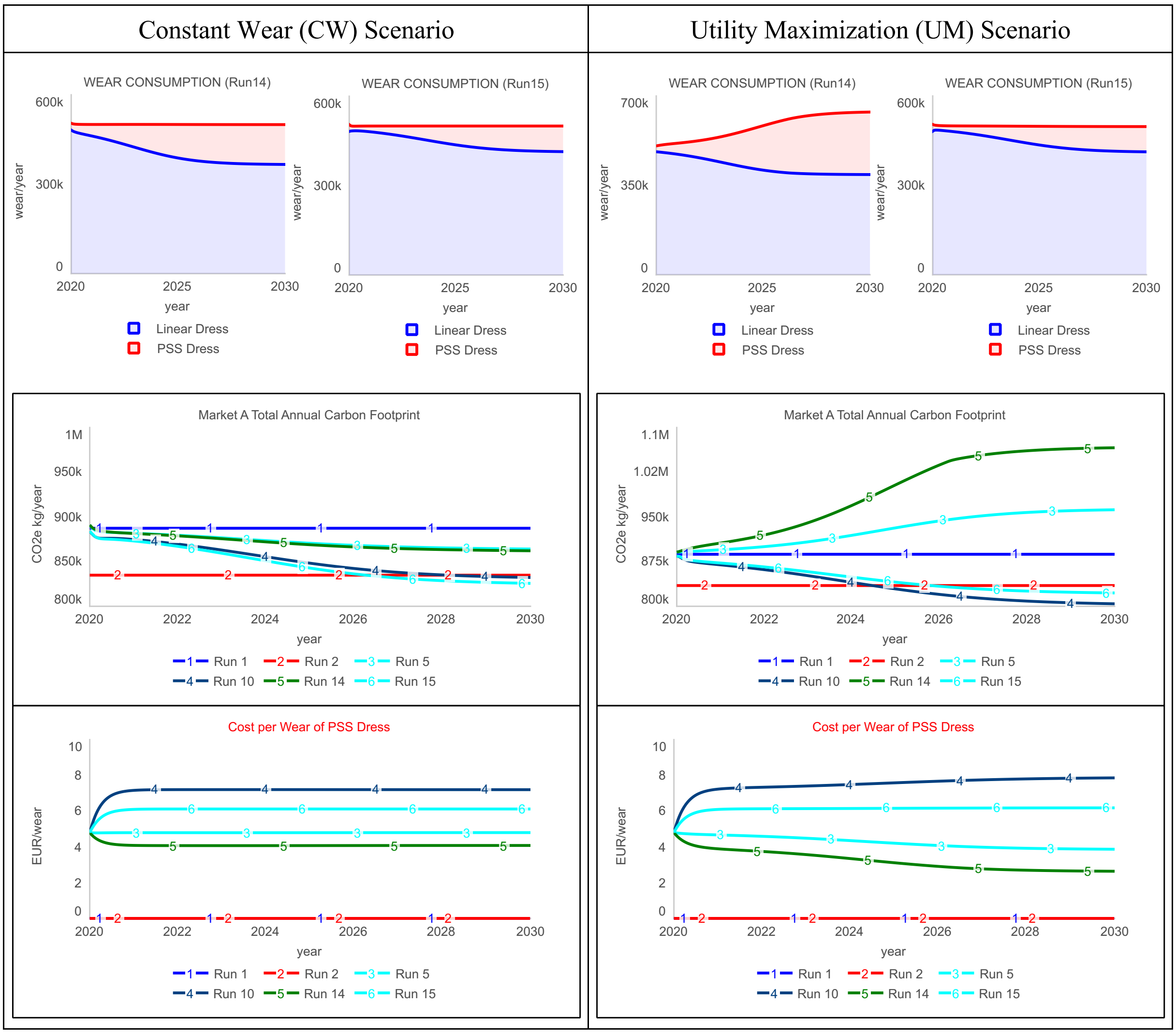


Figure 15 VAT cut for Unlimited swaps/Flat fee (Run5) & Limited swaps/Variable fee (Run10)

When a VAT reduction is applied to Use-PSS platforms that offer unlimited swaps under a flat monthly fee with free shipping, the result of Run 5 shifts to Run 14. Under CW scenario, it results in a slight reduction in the annual carbon footprint because a reduction in CPW_{PSS} results in more substitution from conventional demand. However, under UM scenario, it enhances the extent of Use-PSS rebound, causing a stark backfire. In essence, if a VAT reduction is applied to a membership system that is highly vulnerable to consumer behavior of CW and UM, the gap between the carbon footprint between CW and UM scenario (i.e. the extent of Use-PSS rebound) will be widened, making the system even more vulnerable to consumer behavior.

On the other hand, when a VAT reduction is applied to Use-PSS platforms that offer limited swaps under a variable monthly fee while charging for shipping, the result of Run 10 shifts to Run 15. The result of carbon footprint in Run 15 is almost identical to that of Run 10, both in CW and UM behavior, while the PSS dress becomes more affordable and thus more able to better satisfy the demand of wear (Run 15 compared to Run 10, c.f. ***Figure 13***). Thus, if a VAT reduction is applied to a membership system that is more robust against consumer behavior of CW and UM, this could increase the availability of Use-PSS for clothing while mitigating the risk of rebound. In essence, a VAT reduction results in more substitution under CW scenario and thus would yield more emission saving as long as $IPW_{PSS} < IPW_{Linear}$. However, under UM scenario, taking the direct economic rebound effect into account, the result highly depends on how robust the membership design of a clothing PSS platform is (Run 14 or 15). Therefore the simulation highlights the importance of taking Use-PSS rebound into account as well as selecting the type of membership design to publicly assist, especially when applying economic incentives that affect cost per wear of Use-PSS, such as VAT reduction. Even if the difference in carbon footprint between Run 10 and 15 is rather negligible, VAT reduction could be meaningful to incentivize the best practices, by limiting the application to PSS platforms that implement limited swaps under a variable monthly fee based on actual swap frequency.

5.4 Risk of compromising the lifespan of PSS dress by frequent wash cycles

In alignment with the LCA studies by Sandin et al., (2019) and Zamani, Svanström, Peters, & Rydberg (2015), this study assumes that a linear dress will be washed once in three times of wear. In the forgone scenarios, it was implicitly assumed that the lifespan of PSS dress does not change regardless of how few the WPS is and how frequent the dresses are washed, which is the assumption that has not been challenged in existing LCA studies of clothing PSS (Johnson & Plepys, 2021; Piontek et al., 2020; Zamani et al., 2017). Even if a user wears a dress once and sends it back where the platform washes it professionally, it was assumed to be done so three times more efficient and less harmful (e.g. spotting stains, rather than full dry/wet cleaning) so that each wear attains one-third of a full wash cycle. However, this also requires each subscriber to contaminate less on average when wearing less than three times, while they are highly sensitive to perceived contamination and also odors (Clube & Tennant, 2020). In order to investigate the implication of potential risk of lifespan degradation, a sensitivity test is carried out where every returned PSS dress is assumed to be fully washed, depleting its physical lifespan of 10 washes that can normally facilitate up to 30 wears.

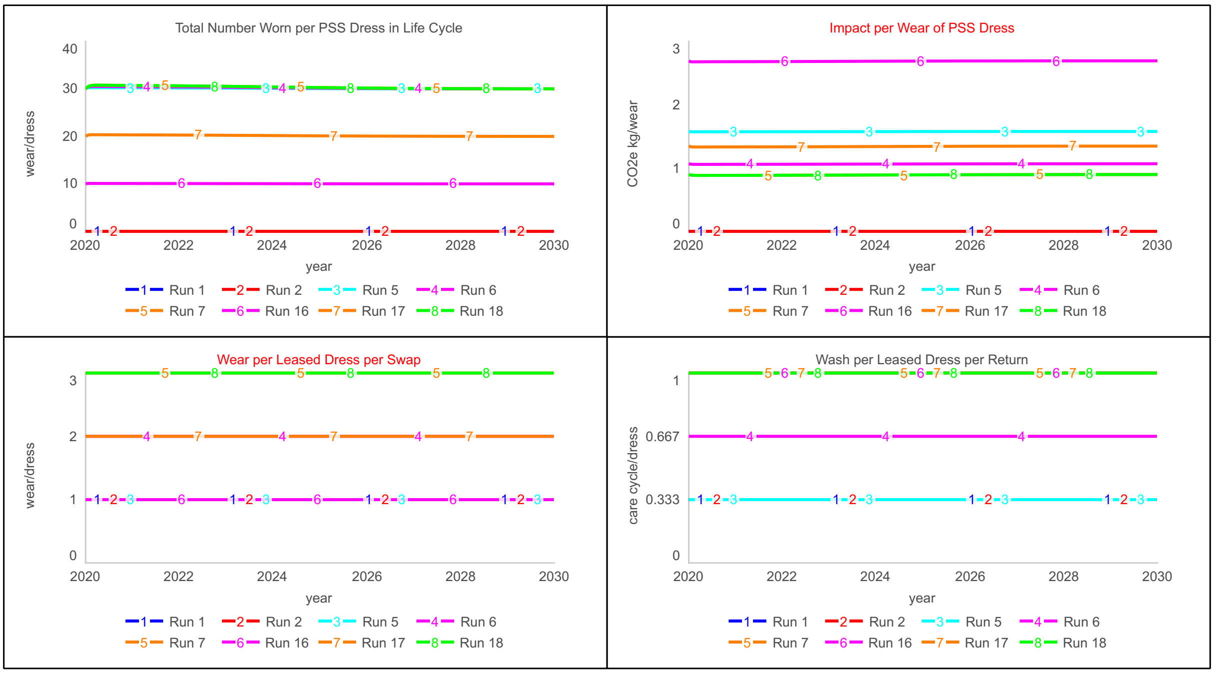


Figure 16 Partial wash according to WPS (Run 5,6,7) to full wash per return (Run 16,17,18)

The physical lifespan in the number of times a rental dress is worn in its life cycle decreases from 30 wear/dress (Run 5,6,7) to 20 wear/dress for Run 17 (WPS =2) and 10 wear/dress for Run 16 (WPS =1). When WPS is three (Run 7 and 18) it bears no change in lifespan since wash frequency will be the same as in the case of linear dress. Taking such lifespan degradation reveals a significant increase in the IPW_{PSS}, especially when WPS is one (Run 16 compared to Run 5), further eliminating the carbon footprint saving potential per substitution of wear, to such a degree that surpasses IPW_{Linear}.

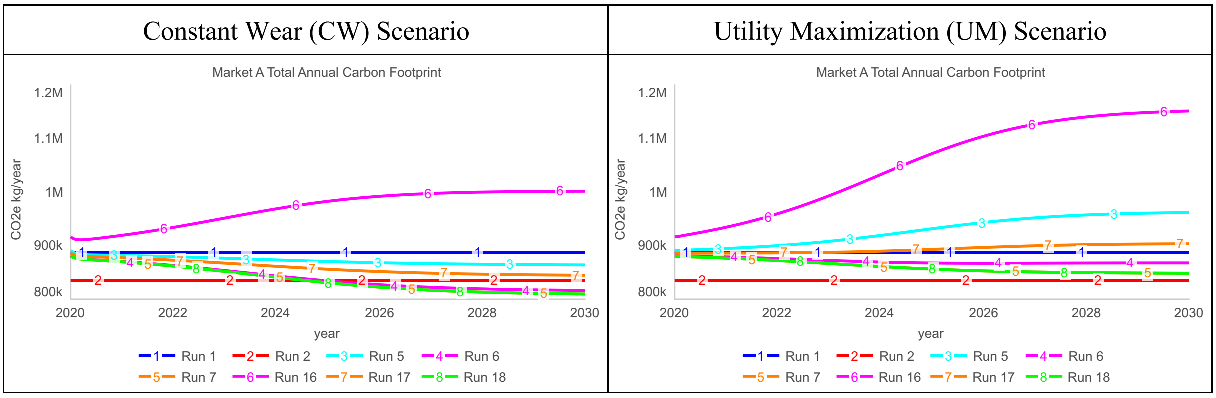


Figure 17 Effect of lifespan erosion by increased wash frequency under Unlimited swaps/Flat fee

The volume of wear demand is the same as Run 5, 6, and 7 for Run 16, 17, and 18, respectively.

The resulting annual carbon footprint is a significant increase from Run 5 to Run 16, and from Run 6 to Run 17 both under CW and UM scenario, where the former case (WPS = 1) is by far more significant. Counterintuitively, such lifespan shortening increases the carbon footprint also under CW scenario even if the total wear demand does not increase (Run 16), because the shortened lifespan of PSS dress jeopardizes the emission saving potential to such a degree that Use-PSS no more entails environmental benefit (i.e. IPW_{PSS} / IPW_{Linear} > 1). This risk is further amplified under UM scenario when combined with Use-PSS rebound. Hence, the sensitivity test demonstrates a potential significance of the wash cycles in relation to the garment lifespan, and further emphasizes the importance of higher WPS, to mitigate the risk of potential lifespan degradation.

5.5 Increasing attractiveness of Use-PSS for clothing

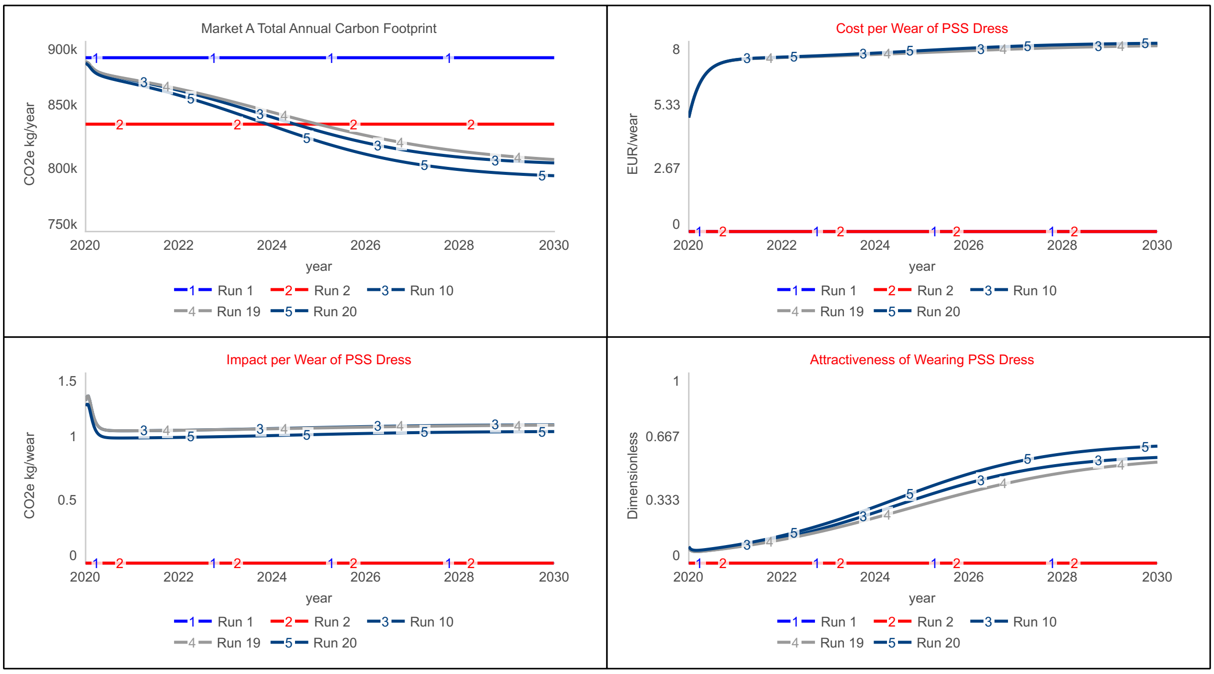


Figure 18 Effect of word of mouth from subscribers & high-quality material use (UM Scenario)

In regard to the attractiveness of wearing PSS dresses, two variations from Run 10 are considered. Run 19 corresponds to the case where the word of mouth effect from PSS subscribers was zero, unlike other simulation runs that assume its presence. Run 20 represents the case when adopting high-quality and sustainable material such as Tencel for clothing PSS, on top of the active word of mouth effect from PSS subscribers. The word of mouth effect from subscribers forms additional reinforcing feedback (Loop R3) and increases the speed of awareness growth from Run 19 to Run 10. Additionally, the adoption of Tencel for clothing PSS is assumed to increase the perceived quality of the PSS dress by 10% and thus increase PSS attractiveness, while reducing the impact per wear, both contributing to more carbon footprint reduction (Run 20 from Run 10). Both Runs 19 and 20 demonstrate that the substitution by PSS can be fostered by increasing its attractiveness rather than reducing the cost per wear, to reduce the carbon footprint while mitigating the rebound effect.

Chapter 6. Conclusion and Discussion

This chapter first answers the research question, then discusses theoretical and practical implications, followed by limitations of this study and suggestions for future research.

6.1 Answers to the Research Questions

RQ1 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint?

Delimiting the scope to the realm of microeconomic clothing consumption, that is, leaving out the indirect and economy-wide rebound effect, the main determinants of the potential of subscription-based Use-PSS of dress to reduce annual carbon footprint are the relative impact per wear of PSS dress compared to that of the reference system (i.e. conventionally sold dress), the magnitude of substitution for conventional demand over one wear of PSS dress (i.e. replacement rate of wear, see formula (2), p.19) and the magnitude of substitution for aggregated conventional demand (i.e. market share). Regarding how the replacement rate of wear and market share is determined, this study took two distinct assumptions regarding the annual consumption of wear, the Constant Wear (CW) and Utility Maximization (UM) scenarios, hence the answers to the sub-questions are given below.

6.1.1 RQ1-1 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint when consumers' demand of wear remained constant?

This question corresponds to the CW scenario, the case where consumers would not change their annual demand of wearing dresses including trial, as they would not demand facilitation of wear more than needed to cover for constant wear occasions. Under this condition, the market share of wearing PSS dress can be increased by an increase in weighted attractiveness (i.e. attractiveness divided by cost per wear) of PSS dress while the total consumption of wearing dress does not change (i.e. replacement rate of wear is always one). Therefore, as long as the impact per wear of PSS dress is lower than that of linear dress, higher attractiveness and lower cost per wear of PSS dress would directly lead to an increase in pure substitution and thus more carbon footprint saving (***Figure 15***). The focus will be thus on how low the relative impact per wear and cost per wear of PSS dress can be, as well as how high the attractiveness and potential penetration rate of wearing PSS dress can be.

Current literature's discussions mainly center around how to ensure lower relative impact per wear of clothing PSS. Critical factors are; 1) high production impact of linear dress, 2) sufficient lifespan extension, 3) multiple times of wear per user per rented dress and 4) minimal transportation impact per shipment.

1) First, since the main carbon footprint saving in Use-PSS arises from avoided production impact, lifespan extension has high environmental potential when the production impact of status quo is high, as in the case of dresses made of virgin polyester. If dresses can be made of sustainable material such as Tencel (Goldsworthy, Earley, & Politowicz, 2018) or paper material prototyped by Peters, Sandin, Spak, & Roos (2018) at a large scale, this could also reduce the carbon footprint meaningfully, providing another possibility of intervention under a linear business model. Such policy may be especially effective in markets where the potential penetration of Use-PSS dress remains low.
2) Second, the active lifespan of dress has to be sufficiently extended (Zamani et al., 2017). This entails that the dresses are heavily underutilized in the status quo and a high maximum lifespan is realistically achievable by Use-PSS. In the case of maternity wear, one has to be careful to take into account that they may be actually highly utilized by sharing among families and friends while non-monetary transactions are not reflected in statistical data (Demailly & Novel, 2014; Kjaer, Pigosso, Niero, et al., 2018). Importantly, PSS garments have to be physically and aesthetically durable by adopting high-quality material and timeless design (Kjaer, Pigosso, Niero, et al., 2018; Piontek et al., 2020), and actually utilized for longer use by mitigating the risks to compromise lifespan extension, such as careless use by customers because of non-ownership (Tukker, 2015), quick turnover based on fashion trend (Borg et al., 2020), and wearing out of durability by increased wash and dry frequency (***Figure 16***) (Kjaer, Pigosso, Niero, et al., 2018).
3) Third, the number of times a rented garment is worn per user (i.e. Wear per Swap, WPS) determines how many times a PSS dress has to be transported, washed, and packaged in its lifecycle and thus has a major impact on the transportation impact per wear (Johnson & Plepys, 2021; Zamani et al., 2017) (***Figure 11***) as well as the physical lifespan of PSS dress if increased wash frequency degrades the garment more than less frequent wash cycles of linear dress (***Figure 16***). An increase in WPS from one to two wears has a high leverage to reduce the transportation impact (Johnson & Plepys, 2021; Zamani et al., 2017) and potential risk of lifespan shortening, as it reduces the logistics and wash cycle frequency by half, significantly increasing the carbon footprint reduction potential (***Figure 16***).

4) Fourth, transportation mode and distance highly matter for impact per shipment, as a clothing library operated via an offline physical store with high impact transportation mode (i.e. private car) can cause about twice as much carbon footprint compared to an online operation with a low impact transportation mode (i.e. using bus to a pickup point) (Roos et al., 2015; Zamani et al., 2017).

As for the attractiveness of Use-PSS for clothing, it develops gradually over time (***Figure 18***) since it involves an innovative consumption style and it is more attractive for those who have a higher fashion consciousness and awareness towards PSS (***Figure 10***).

Importantly, under the CW scenario, as long as the impact per wear of PSS dress is lower than that of linear dress, carbon footprint can be reduced more by lowering the cost per wear of PSS dress as it leads to more substitution of conventional demand. Moreover, since the total demand for wearing dress remains constant, PSS subscribers would not increase the consumption of wear more than necessary, even under a membership system offering unlimited swaps. Thus, under a CW scenario, platform strategies or public policies to enhance the price competitiveness of PSS (e.g. application of reduced VAT rate for PSS businesses) would make sense to reduce the annual carbon footprint (***Figure 15***).

6.1.2 RQ1-2 What is the market-mediated potential of subscription-based Use-PSS of dress to reduce annual carbon footprint when economic rebound effect is taken into account?

This question corresponds to UM scenario, the case where the consumers would maximize the annual consumption of wear (including trial) of dress within the constant level of clothing expenditure to maximize their utility from fashion consumption. Under this condition, the market share of wearing PSS dress is still determined by the relative weighted attractiveness of PSS dress. However, the total amount of consumption of wear also changes according to the affordable facilitations of wear of dress per year. Therefore, while higher attractiveness of wearing PSS dress increases substitution for linear dress and thus more carbon footprint saving, lower cost per wear of PSS dress would increase the annual demand of wearing dresses. This will offset the emission saving as a result of the direct economic rebound effect (***Figure 15***), even when the impact per wear of PSS dress is lower than that of linear dress. The focus will be thus on how low the relative impact per wear of PSS dress can be, as well as how high the attractiveness and potential penetration rate of wearing PSS dress can be, while keeping the cost per wear of PSS dress as high as that of linear dress as possible.

Importantly, in the UM scenario, consumers would increase the consumption of wear as long as it is affordable, meaning the replacement rate of wear will be lowered by a reduction in the relative cost per wear of PSS dress. Hence, under this condition, it is required that the relative impact per wear of PSS dress is lower than the replacement rate of wear (see formula (2), p.19) to yield a net carbon footprint saving compared to the status quo.

In summary, under the UM scenario, a reduction in the price of PSS causes a rebound or in the worst case a backfire, where the emission saving is partially offset or the emission even increases. Such risk is the greatest for membership systems offering unlimited swaps under a flat monthly fee and free shipping and washing, and especially when consumers' desired WPS is low (***Figure 12 & 15***). Linking the actual swap frequency to monthly fee is not only effective to incentivize minimum transactions (Zamani et al., 2017) but also to mitigate the risk of rebound, since it formulates a balancing feedback loop that increases the cost per wear when the hyper-consumption loop activates through increased swap frequency (Loop B6b) (***Figure 13***). Carbon footprint reduction potential of Use-PSS of dress can be increased while mitigating rebound effects, by focusing on increasing its unique attractiveness (e.g. by offering access to higher quality garments, increasing awareness towards PSS, offering personal style consulting, etc.) rather than relying on the lower price of PSS, so that the conventional demand can be shifted towards consumption with higher satisfaction within a similar expenditure level, which aligns with the notion of "eco-efficient value creation" (Scheepens et al. 2016:259).

6.2 Theoretical Implications

Use-PSS for clothing has been hoped as one of the promising approaches to fundamentally alter the current wasteful linear fashion consumption. Although clothing rental subscription has recently become increasingly popular, business is still challenging because of high cost and still low market acceptance by general consumers, calling for public interventions. In the academia, LCA studies identified that Use-PSS for clothing entails both the potential for a reduction but also an increase in environmental impact, heavily depending on consumer behavior, however, the focus has been on the impact per wear of clothing PSS under the assumption of constant total demand of wear (Johnson & Plepys, 2021; Piontek et al., 2020; Zamani et al., 2017), leaving out the consideration of direct rebound effect. Meanwhile, other literature qualitatively point to the potential of hyper-consumption by CFC and other risks such as compromised lifespan (Armstrong & Park, 2020; Borg et al., 2020; Demailly & Novel, 2014; Iran & Schrader, 2017; Kjaer, Pigosso, Niero, et al., 2018; Tukker, 2015), which have still not reflected in LCA studies of Use-PSS for clothing.

In order to address the knowledge gap, this study challenged the assumption of constant demand for wearing dresses by conceptually demonstrating a what-if analysis by a system dynamics model as a "conceptual virtual laboratory" (de Gooyert, 2019:660). The concept of "consumption-as-usual" (Girod, De Haan, & Scholz, 2011:3) and "circular economy rebound" (Zink & Geyer, 2017:593) were used to help model consumers' UM behavior, while I extended the application of the latter to the context of Use-PSS for clothing, termed Use-PSS rebound in this thesis. Key theoretical implications are derived as follows.

6.2.1 Relative price advantage as a double-edged sword (Use-PSS rebound)

By taking the economic rebound effect into account, ***Figure 15*** demonstrates that a reduction in cost per wear of Use-PSS dress is a double-edged sword held by consumers in terms of carbon footprint reduction. Thus, the study poses a caution to public policies to enhance the price competitiveness of PSS (e.g. VAT reduction for clothing PSS) (Ecopreneur.eu, 2019; Elander et al., 2017) without considering the diversity of membership design of Use-PSS for clothing, or marketing strategies putting clear emphasis on the relative advantage of money-saving by Use-PSS (Park & Joyner Armstrong, 2019; Tao & Xu, 2020) if the primary purpose of Use-PSS for clothing is to foster environmental impact reduction.

For one hand, this finding supports the notion of Girod et al. (2011) and Kjaer, Pigosso, McAloone, et al. (2018) who point to the importance to take potential rebound effect into account in LCA, especially when policies affect the "consumption factors" (Kjaer et al., 2018:670) (e.g. money, time, space and access, etc.) needed for the consumption of product and services. Identifying and assessing differences in consumption factors (i.e. cost per wear in this study) helps to assess more realistic substitutability in the eyes of consumers and potential for rebound effects since it becomes the origin of rebound effects (Kjaer et al., 2017; Kjaer, Pigosso, McAloone, et al., 2018). However, this dimension has been not yet discussed in LCA studies under the context of Use-PSS for clothing.

Johnson & Plepys (2021) empirically investigated the degree of substitution for wear occasions of linear formal dress by rental formal dress and found that on average they were willing to substitute 70% of their conventional wear occasion by rental dress. However, the concept of replacement rate in their study was used as a degree of substitution under a constant number of wear occasions, and therefore rather functioned as a penetration rate. Following the definition of the replacement rate by Farrant, Olsen, & Wangel (2010:728) and Nørup, Pihl, Damgaard, & Scheutz (2019:1026) however, a replacement rate lower than one inherently means an increase in overall consumption and thus a direct rebound effect. Thus, the modeling of the substitution by Johnson & Plepys (2021) can be interpreted as assuming a replacement rate of wear of one, applied to the fraction (i.e. penetration rate) of conventional demand based on constant total wear occasions. This is a reasonable approach for the pay-per-use model of formal dress in their study, since the majority of users indicated they would not increase usage of rental even if the rental shop provided unlimited swaps (Johnson & Plepys, 2021).

However, on the other hand, Use-PSS rebound should be also taken into account when a clothing rental subscription offers a high number of swap opportunities for the users who are highly willing to experiment with a variety of styles. Trial opportunities could unexpectedly increase consumption beyond the usual needs of function and thus increase environmental impact (Allais & Gobert, 2017). It entails the risk of phantom wear, where one facilitation of wear of PSS dress does not cover for an actual wear occasion (i.e. replacement rate of wear < 1), while equally requiring shipment, packaging, and industrial cleaning to facilitate each wear for users, causing environmental impact but also physical degradation of a garment. Examples of additional backup dress (McKinney & Shin, 2016) or frequent mismatch in fashion SOS (Niehm, 2020) imply the occurrence of such phantom wear which increases the risk of Use-PSS rebound, which is overlooked in existing LCA studies.

Finally, the notion that the relative price advantage is a double-edged sword highlights the emphasis on the unique attractiveness of Use-PSS for clothing rather than its price advantage. Priority should be on strategies that both enhance the perceived attractiveness of PSS while reducing its environmental impact, as Scheepens, Vogtländer, & Brezet (2016:261) suggest with their concept of the "double objective" of the eco-efficient value creation. One example of this is the adoption of high-quality sustainable material such as Tencel as demonstrated in (***Figure 18***), or style consultancy services discussed in practical implications.

6.2.2 Role of membership design to mitigate rebound, increase WPS

It was found that the carbon footprint saving potential of Use-PSS for clothing depends highly on the design of membership. ***Figure 12 & 15*** showed that the risk for hyper-consumption is the greatest for platforms that offer unlimited swaps under a flat monthly fee, without charging transaction cost. On the contrary, under the variable monthly fee based on transaction frequency with limited maximum items accessible per month, the outcome of the annual carbon footprint became more robust against consumer behavior (***Figure 13***). This supports the suggestion by Zamani et al. (2017) to make users pay for each transaction, as it reduces the affordable demand of wearing PSS dress per month and thus reduces swap frequency (Loop B6b). However, rather than minimizing transportation impact, linking swap frequency to monthly fee is important in the sense that it formulates a balancing feedback loop to regulate hyper-consumption, thereby makes the membership design more robust against consumer behavior.

Since WPS is an important factor for environmental potential and to induce a higher number of WPS, Johnson & Plepys (2021) recommended businesses to avoid a pay-per-single use scheme and Zamani et al. (2017) suggested offering fewer items available per user at a time in a longer lease period. The result in ***Figure 14*** aligns with the suggestion by Zamani et al. (2017) to offer a longer lease period, which translates to a fewer max swap frequency, to induce an increased number of WPS. Also, ***Figure 25*** (Appendix 6) supports the suggestion by Zamani et al. (2017) to limit the max items at a time since it is necessary to limit the total availability of PSS dress in order to induce higher WPS.

Still, only membership design has limitations to induce increased WPS. Even if both the max swap frequency and the max items at hand were low (e.g. 2 swaps per month and three items at a time), ***Figure 25*** (Appendix 6) shows that WPS could still be small if there is not a sufficient demand per month, highlighting a limitation of membership design. It corresponds to the consideration by Johnson & Plepys (2021) that inducing higher WPS is difficult for formal dress since the wear occasions are dispersed. This calls for more proactive measures to increase WPS to increase the environmental potential of Use-PSS for clothing.

6.2.3 Risk of reduced lifespan due to increased wash cycle frequency

Wash cycles (i.e. washing, drying, and ironing) degrade the physical lifespan of clothing (McQueen, Batcheller, Moran, Zhang, & Hooper, 2017) more than the act of wearing itself (Petersen & Riisberg, 2017), therefore a reduction in the number of wears before each wash cycle leads to more frequent wash and thus shorter physical lifespan (Laitala & Klepp, 2020). Surprisingly though, even though Use-PSS potentially (Iran & Schrader, 2017; Piontek et al., 2020; Zamani et al., 2017) and actually (Johnson & Plepys, 2021) increases the wash frequency of rental garments compared to owned items, its risk of shortening the lifespan of Use-PSS garment has been only qualitatively referred by Blüher et al. (2020) and left out from the calculation of LCA of Use-PSS for clothing, as wash cycles per se have a negligible impact even if the wash frequency increases (Johnson & Plepys, 2021; Piontek et al., 2020; Zamani et al., 2017). However, the importance of wash cycles probably lies in their frequency and potential effect on the lifespan of garments, rather than the impact per wash cycle itself. A sensitivity test to check the effect of increased wash cycles on the lifespan of PSS dress (***Figure 16 & 17***) revealed that a frequent wash cycle could jeopardize the carbon footprint saving potential even under a CW scenario, if increased wash frequency leads to a reduction in lifespan of PSS dress, and even more so under UM scenario where the risk is amplified by Use-PSS rebound and phantom wearing. In order for increased wash cycles to have a neutral effect on the physical lifespan of dresses, it requires that the users contaminate less when wearing for only once, and platforms to wash such dresses three times less damaging, which is arguably a tough requirement considering the business model's very high priority on perceived hygiene (Borg et al., 2020; Clube & Tennant, 2020). Some users might even voluntarily wash received items extra before use (Zamani et al., 2017) as they usually do when having bought second-hand clothing (Armstrong & Park, 2020) or when they perceived the rented clothes to be not clean enough (Clube & Tennant, 2020). This further emphasizes the importance of higher WPS as it also mitigates the risk of lifespan shortening (***Figure 16***).

It might be also well the case that such shortening of physical lifespan does not matter for dresses, since the inventory is renewed based on fashion and social lifespan even under the context of Use-PSS (Borg et al., 2020). In such a case, it is still encouraged to contrast against best practices where dresses are used until their very maximum of technical durability, to grasp the degree of compromised lifespan extension and potential for further reduction in impact per wear.

6.2.4 Summary of theoretical contribution

This study highlights the importance to take the direct economic rebound effect into account when assessing the robustness of membership design of clothing PSS against hyper-consumption as well as the carbon footprint saving potential of public intervention that affects the cost per wear such as VAT reduction. To increase the environmental potential, the importance of a higher number of WPS and to enhance the unique attractiveness of Use-PSS for clothing rather than its price competitiveness are emphasized. Together, it highlights the necessity to draw a clear line regarding which platforms to assist via public intervention, and increases understanding of possible criteria for such judgments. The study also illustrates the potential significance of phantom wear and compromised lifespan due to increased wash frequency, which has not gained attention in the literature. Consequently, the study encourages to incorporate the effect of cost per wear on replacement rate of wear in LCA by carrying out sensitivity tests with variations in total wear demand and to empirically study the occurrence and the extent of Use-PSS rebound, phantom wear, and the effect of increased wash frequency on lifespan of PSS clothing.

6.3 Practical Implications

Taking the direct economic rebound effect into account highlights the importance of unique PSS attractiveness, higher number of WPS, and membership design that induces it and mitigates hyper-consumption. These theoretical implications lead to the following recommendations.

6.3.1 Limiting the max swap frequency and max items at a time, as well as reflecting actual transaction cost upon the basic monthly fee of each subscriber

It is recommended to phase out from offering unlimited swaps based on a flat-rate monthly fee, as it implicitly incentivizes subscribers to increase the swap frequency in order to make the best of the subscription rental (Pedersen & Netter, 2015) and opens up the possibility for hyper-consumption if combined with consumers' UM behavior. Rather than that, it is important to give them flexibility to increase their wear demand in such a way that they pay extra for an increase in transaction. Linking the actual swap frequency to the monthly fee is required not only to incentivize each subscriber to minimize swap frequency but also to form a balancing loop (Loop B6b) that regulates the hyper-consumption loop (Loop R4b). Still, it is important to technically limit the max swap frequency to eliminate the chances of high-frequency swaps by few subscribers who can still afford the highest variety. At the same time, the max items at a time has to be small enough to induce a higher number of WPS. This strategy would also help business operation, since frequent renewal of inventory and reverse logistics are significant challenges for inventory and cost management (Gilliot, 2019; Hvass, 2015).

6.3.2 Fostering word of mouth from subscribers

Fostering communication from subscribers can create an additional reinforcing feedback loop (Loop R3) that could powerfully speed up the diffusion of awareness towards PSS, thus helping to increase the attractiveness of PSS faster (***Figure 18***). PSS platforms such as MUD Jeans also stress the importance of communication for awareness building (Wijnen & Groenestege, 2020) in terms of strengthening customer loyalty and widening the customer base.

6.3.3 High quality and sustainable material

Switching from virgin polyester to a more sustainable and higher quality material such as Tencel is recommended since it could both enhance perceived fabric quality (McKinney & Shin, 2016) and thus attractiveness of PSS dress while reducing its environmental impact, in alignment with the principle of eco-efficient value creation (Scheepens et al., 2016). Tencel has an excellent technical durability and functionality along with silky touch compared to cotton (Basit et al., 2018; Good on You, 2020; Karthikeyan et al., 2016) and its high aesthetic quality has been demonstrated by Filippa K (Goldsworthy et al., 2018). Since it is an expensive material and less affordable for consumers at conventional retail, Use-PSS may offer a unique opportunity to experience higher quality garments for users, while potentially helping platforms to differentiate themselves from peers by other criteria than subscription price (Gilliot, 2019).

6.3.4 Personal style consultancy service combined with Use-PSS for clothing

An in-store or online personal style consultancy service, where "consumers may receive advice about how to continue to wear their existing wardrobe in new and different ways" (Lang & Armstrong, 2018:577) could be another strategy of eco-efficient value creation (Kjaer, Pigosso, Niero, et al., 2018; Scheepens et al., 2016). It could add unique intangible value to a Use-PSS platform while proactively increasing the WPS of rented clothes as well as mitigating the risk of compromising utilization of already owned clothing. Personal styling aims to fulfill customer's unique needs and well-being through a highly interactive process and differs from commercial styling where the central aim is to increase sales of retailer's products (Pöllänen, Parkko, & Kaipainen, 2019), which is the current predominant practice in styling and curation service offered by fashion SOS (Armstrong et al., 2016; Niehm, 2020; Woo & Ramkumar, 2018). Studies by Armstrong et al. (2016) and Lang & Armstrong (2018) indicate positive attitude of consumers towards such interactive personal styling if made available for average consumers, as they wanted creative ideas to combine items in new ways aesthetically rather than buying new clothes, to satisfy their desire for change.

6.3.5 Role of the public sector: identify best practices first and provide incentives

Unlike repair of second-hand clothing, Use-PSS for clothing is far more diverse in their operation and target consumer types. Applying VAT reduction to all Use-PSS for clothing without considering the diversity of membership design has a high risk to jeopardize carbon footprint saving potential because of rebound or backfire (***Figure 15***) while requiring significant loss of tax revenue (Watson, Gylling, & Thörn, 2017). Instead, the priority for the public sector should be first to identify best practices (Demailly & Novel, 2014) to pinpoint which model is eligible for support and to effectively promote such models in less budget.

At the same time, limiting the maximum items available per subscriber per month (i.e. limiting max item at hand and max swap frequency) and making subscribers pay for each transaction cost may be challenging for an individual PSS platform to implement under a real market context, where platforms are competing to offer more price advantage, variety and convenience to potential customers to expand the market share (Gilliot, 2019).

It is thus suggested to incorporate membership designs that are robust against consumer behavior and certified LCA results into a minimum criteria to distinguish who is eligible for public economic incentives. For example, applying VAT reduction only to businesses that limit the max swap frequency of twice per month while reflecting each transaction cost on monthly fee, could promote accessibility of Use-PSS while mitigating the risk of rebound (***Figure 15***), rewarding and incentivizing such membership design and save public budget required. Also, personal style consultancy services require high labor costs (Armstrong et al., 2016) and thus are likely to be challenging to implement voluntarily. Public sectors could promote them by wage subsidies (Watson et al., 2017), as well as carry out research on the effect of such personal style consultancy on WPS, which is a critical determinant to the environmental impact reduction potential of Use-PSS for clothing.

6.4 Limitations and suggestion for future research

6.4.1 Transportation impact

Critically, the study assumes the same impact of transportation for volume and distance, that is, there is no difference between higher frequency with lower volume, and lower frequency with higher volume logistics. LCA guidelines suggest that if the transportation efficiency drops, it results in an increased impact (Zampori & Pant, 2019), which is obviously the case with passenger cars (Johnson & Plepys, 2021). In such a case, within the same max accessible items per month, higher max items at a time with lower max swap frequency could be more recommended than lower max items at a time with higher swap frequency. This should be further studied in future research.

6.4.2 Operation cost of businesses

In the model, the operation cost of businesses are excluded. However, in reality, there needs to be a large initial investment and inventory to facilitate rental, and there are tipping points and critical masses to be met in order to run PSS businesses. Limiting the availability of maximum items accessible per month or retaining a higher price point might be thus challenging for start-ups. Moreover, even though Use-PSS for clothing is a new phenomenon that is on the rise, this study does not reflect the effect of the economy of scale, which can form an important reinforcing feedback loop (Sterman, 2000) that might further facilitate a hyper-consumption at an industrial scale. Such systemic effects should be also taken into account when assessing the long-term environmental potential of public interventions.

6.4.3 Application of Cobb-Douglas utility function

Cobb-Douglas utility function was adopted to model the UM behavior, however this is an obvious simplification that was applied to help model direct economic rebound in the simplest manner possible. Importantly, the utility function (i.e. formula (4)) assumes that both linear dress and PSS dress are normal goods. However, PSS dress might be rather inferior goods in the eyes of general consumers when compared against linear dress. Also, the Cobb-Douglas utility function assumes a cross-price elasticity of zero, meaning a change in cost per wear of PSS dress has no effect on linear dress, under UM scenario. Although this assumption was relaxed in the CW scenario, a more realistic consumer utility function should be studied and applied to model the economic rebound effect, preferably based on empirical consumer studies.

6.4.4 Scope of rebound effect

6.4.4.1 Indirect economic rebound

Indirect rebound, as well as macro-economic level rebound, was out of the scope of this study. However, the former might be important if Use-PSS for clothing generates significant economic savings while no additional wearing of dress is needed, such as in the case of high-end formal dress. In the EU context, the indirect rebound effect caused by clothing could strongly offset (e.g. as much as 75%) the emission saving since clothing has relatively lower carbon intensity compared to other categories of household consumption such as food and transport (Wood et al., 2018). This risk can be however reduced by mitigating the risk of direct economic rebound since they both originate from saved money, hence the recommendations of this study still apply.

6.4.4.2 Rebound due to other freed resources

Rebound effects can also arise from other types of freed resources, such as time and space. Use-PSS for clothing might be also highly relevant to saved space (i.e. wardrobe remains clean) and time (i.e. saving time for shopping) or even mental rebound (i.e. the perception of green might induce Use-PSS rebound), which deserve attention in future research.

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Appendix

Appendix. 1 Source of Causal Relationships

Cause	Polarity	Effect	Source
PSS subscribers	+	Awareness towards clothing PSS	(Lee & Chow, 2020) (Tu & Hu, 2018)
Awareness towards clothing PSS	+	Attractiveness of wearing PSS dress	(Lee & Chow, 2020) (Lee & Huang, 2020) (Pantano & Stylos, 2020) (Pedersen & Netter, 2015) (Tu & Hu, 2018)
Relative variety in fashion by wearing PSS dress	+	Attractiveness of wearing PSS dress	(Armstrong et al., 2016) (Gilliot, 2019) (Johnson, 2020) (Johnson & Plepys, 2021) (Mukendi & Henninger, 2020) (Pantano & Stylos, 2020) (Park & Joyner Armstrong, 2019) (Pedersen & Netter, 2015)
Importance of variety in fashion for consumers	+	Attractiveness of wearing PSS dress	(Gilliot, 2019) (Johnson, 2020) (Johnson & Plepys, 2021) (Lang, Armstrong, & Liu, 2016) (Lee & Huang, 2020) (Park & Joyner Armstrong, 2019) (Shrivastava et al., 2021)
Relative quality (aesthetic and physical) of PSS dress	+	Attractiveness of wearing PSS dress	(Armstrong et al., 2016) (Becker-Leifhold & Iran, 2018) (McKinney & Shin, 2016) (Mukendi & Henninger, 2020) (Niehm, 2020) (Pantano & Stylos, 2020) (Park & Joyner Armstrong, 2019)
Cost per wear of PSS dress	−	Weighted attractiveness of wearing PSS dress	(Armstrong et al., 2016) (Becker-Leifhold & Iran, 2018) (Besanko & Braeutigam, 2020) (Lee & Chow, 2020) (Mukendi & Henninger, 2020)

			(Pantano & Stylos, 2020) (Park & Joyner Armstrong, 2019) (Tao & Xu, 2020)
Weighted attractiveness of wearing PSS dress	+	Market share of wearing PSS dress	(Becker-Leifhold & Iran, 2018) (Besanko & Braeutigam, 2020) (Sterman, 2000) (Yin, 2001) (WRAP, 2012)
Cost per wear of PSS dress	–	Annual demand of wearing PSS dress per subscriber	(Besanko & Braeutigam, 2020) (Yin, 2001)
Weighted attractiveness of wearing PSS dress	+	PSS subscribers	(Armstrong et al., 2016) (Becker-Leifhold & Iran, 2018) (Lee & Chow, 2020) (Park & Joyner Armstrong, 2019) (Tao & Xu, 2020)
Max items accessible per month per subscriber	–	Wear per leased dress per swap (WPS)	(Johnson & Plepys, 2021) (Zamani et al., 2017)
Wear per leased dress per swap (WPS)	–	Number of customers per PSS dress	(Johnson & Plepys, 2021) (Zamani et al., 2017)
Wear per leased dress per swap (WPS)	–	Actual swap frequency of items	(Zamani et al., 2017)
Actual swap frequency of items	+	Monthly fee per subscriber	(Zamani et al., 2017)
Annual demand of wearing PSS dress per subscriber	–	Cost per wear of PSS dress	(Pedersen & Netter, 2015)
Number of customers per PSS dress	+	Annual PSS dress shipment order rate	(Johnson & Plepys, 2021) (Zamani et al., 2017)
PSS dress shipment order rate	+	Transportation impact	(Johnson & Plepys, 2021) (Zamani et al., 2017)
PSS dress return rate	+	PSS dress washing rate	(Iran & Schrader, 2017) (Piontek et al., 2020)
Consumers' degree of utility maximization behavior	+	Annual demand of wearing PSS dress per subscriber	(Demailly & Novel, 2014) (Girod et al., 2011) (Iran & Schrader, 2017)
PSS dress washing rate	+	PSS dress wear out disposal rate	(Laitala & Klepp, 2020) (McQueen et al., 2017) (Petersen & Riisberg, 2017)

Table 2 Source of causal relationships derived from literature

Appendix. 2 Model Overview as a CLD

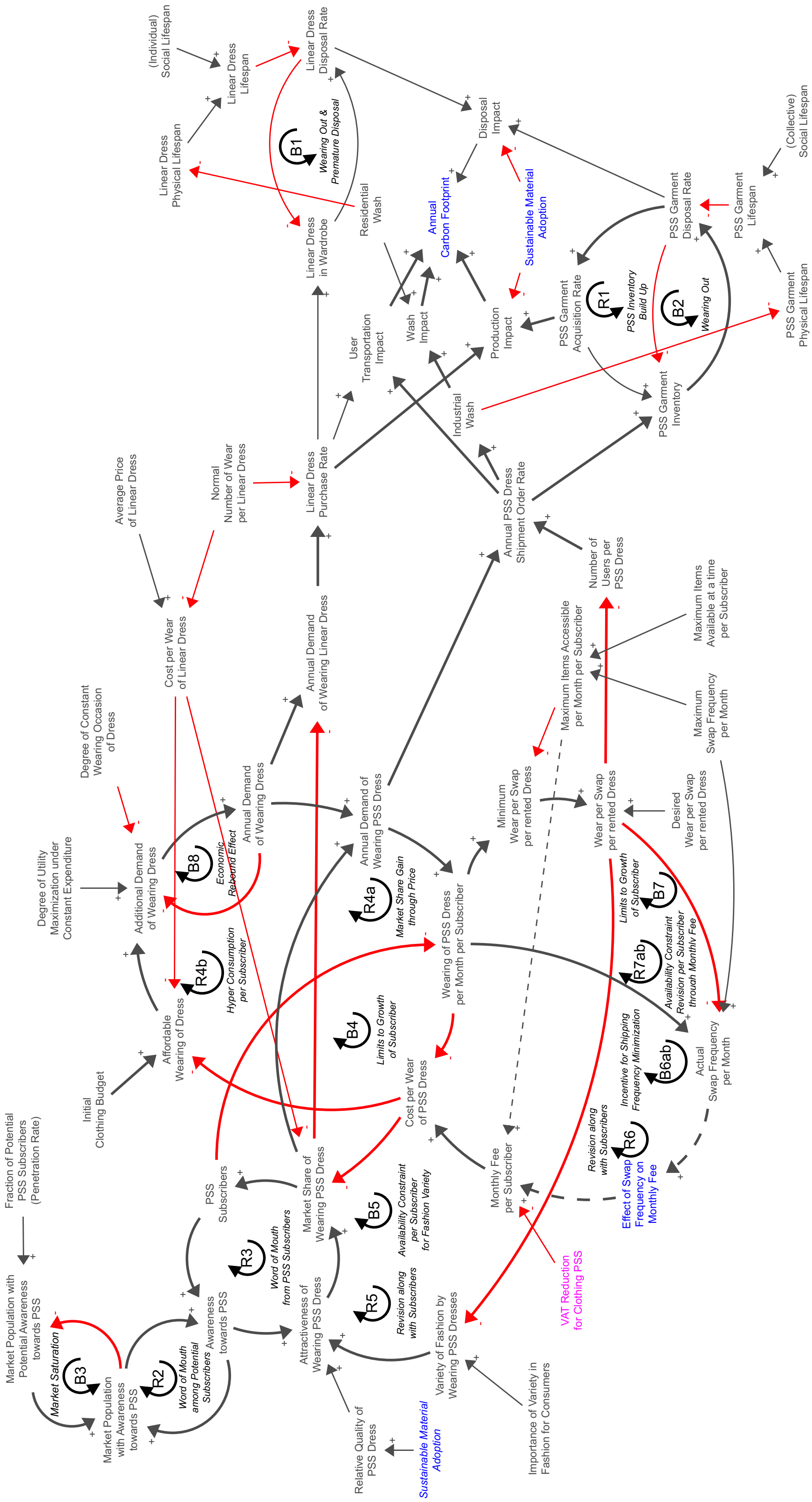

Figure 19 Overview of the model as a CLD

Appendix. 3 Model Boundary Chart

Category	Endogenous	Exogenous	Excluded
Demand of Wear	Annual Demand of Wearing PSS Dress	Initial Annual Wear Occasion of Dress per Person	
	Annual Demand of Wearing Linear Dress	Initial Linear Dress Purchase Rate per Person	
Price and Expenditure	Annual Clothing Budget of Potential Subscribers	Initial Annual Dress Expenditure per Person	Cost of Operation of Linear
	Cost per Wear of PSS Dress	Cost per Wear of Linear Dress	Cost of Operation of use-PSS
Attractiveness of PSS	Attractiveness of Wearing PSS Dress	Attractiveness of Wearing Linear Dress	
	Awareness towards PSS	Effect of Dress Quality on PSS Attractiveness	
	Relative Fashion Variety of Wearing PSS Dresses		
PSS Subscription	PSS Subscribers	Average Subscription Months per Year (Active Wearing Month)	
	Monthly Fee per Subscriber	Reference Monthly Fee	
		Individual Price per PSS Dress per Month	
	Actual Swap Frequency per Month	Max Swap Frequency per Month	
		Max Items Available at a time per Subscriber	
	Actual number of wears per rented dress per swap (Actual WPS)	Desired number of wears per rented dress per swap (Desired WPS)	
Consumer Characteristics		Population of Market A	
		Fraction of Potential PSS Subscribers (Potential penetration rate)	
		Initial Share of Population with Awareness towards PSS	
		Importance of Variety in Fashion for consumers	
		Dominance of Wear Occasion over Demand of Wear	Utility of Wearing Dress
		Dominance of Budget Constraint over Demand of Wear	Effect of other saved resources (time, space, etc.) on wear demand
LCA Data on Carbon Footprint		Carbon Footprint of Cradle to Gate (e.g. production), User Travel, Wash Cycle, and Disposal Phases	Other Impact Categories (e.g. Water Scarcity, Land Use, Toxicity, etc.)
Garment related parameters		Wear per Wash of Dress	
		Physical Durability (Washes Tolerated) of Dress	
		Social Lifespan of Dress	
		Normal Number of Wear per Linear Dress	

Table 3 Model boundary chart

Appendix. 4 Overview of the Quantitative Simulation Model

Appendix.4.1 Overview of the Market A

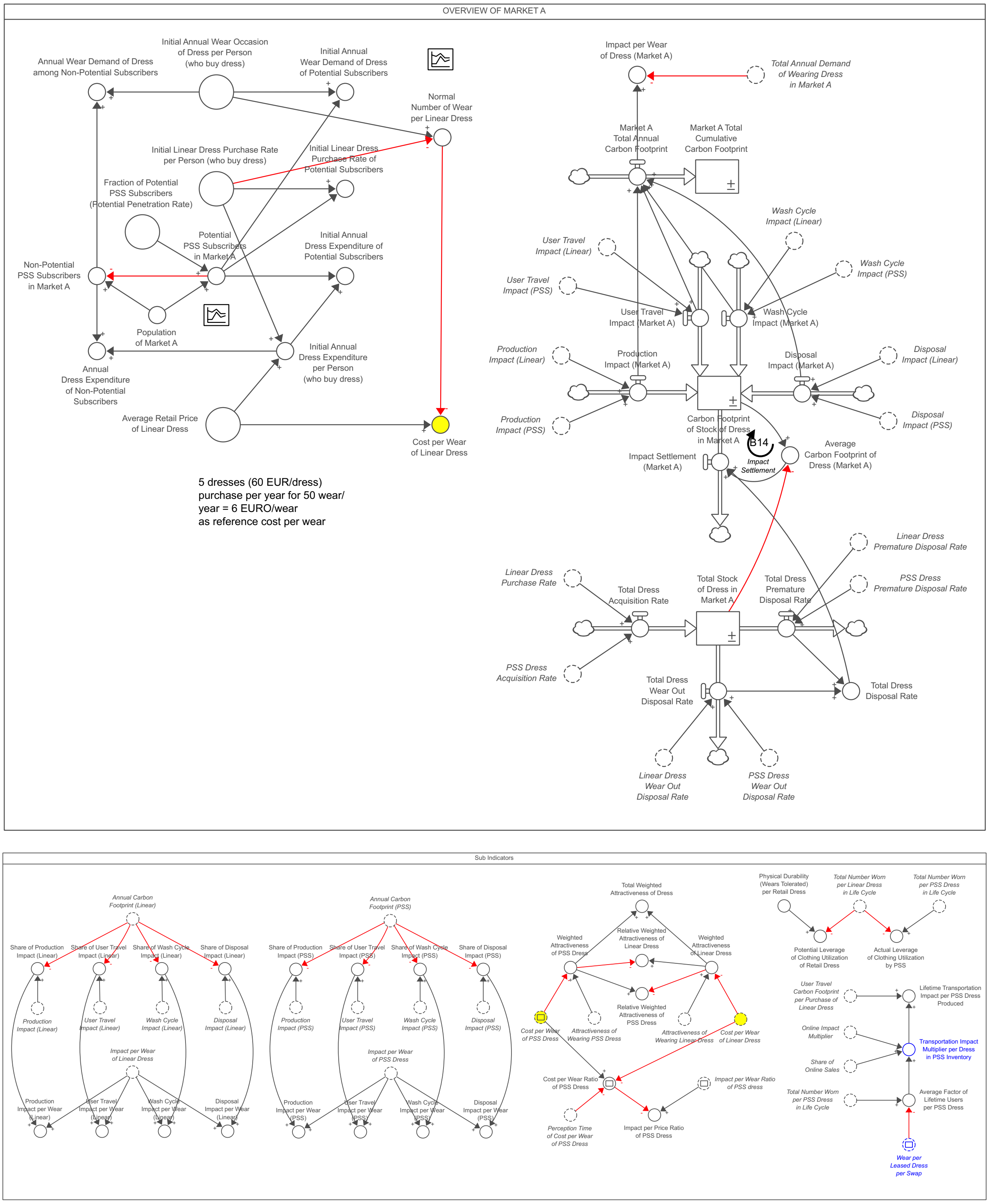

Figure 20 Overview of the Market A

Appendix.4.2 Linear dress and PSS dress module

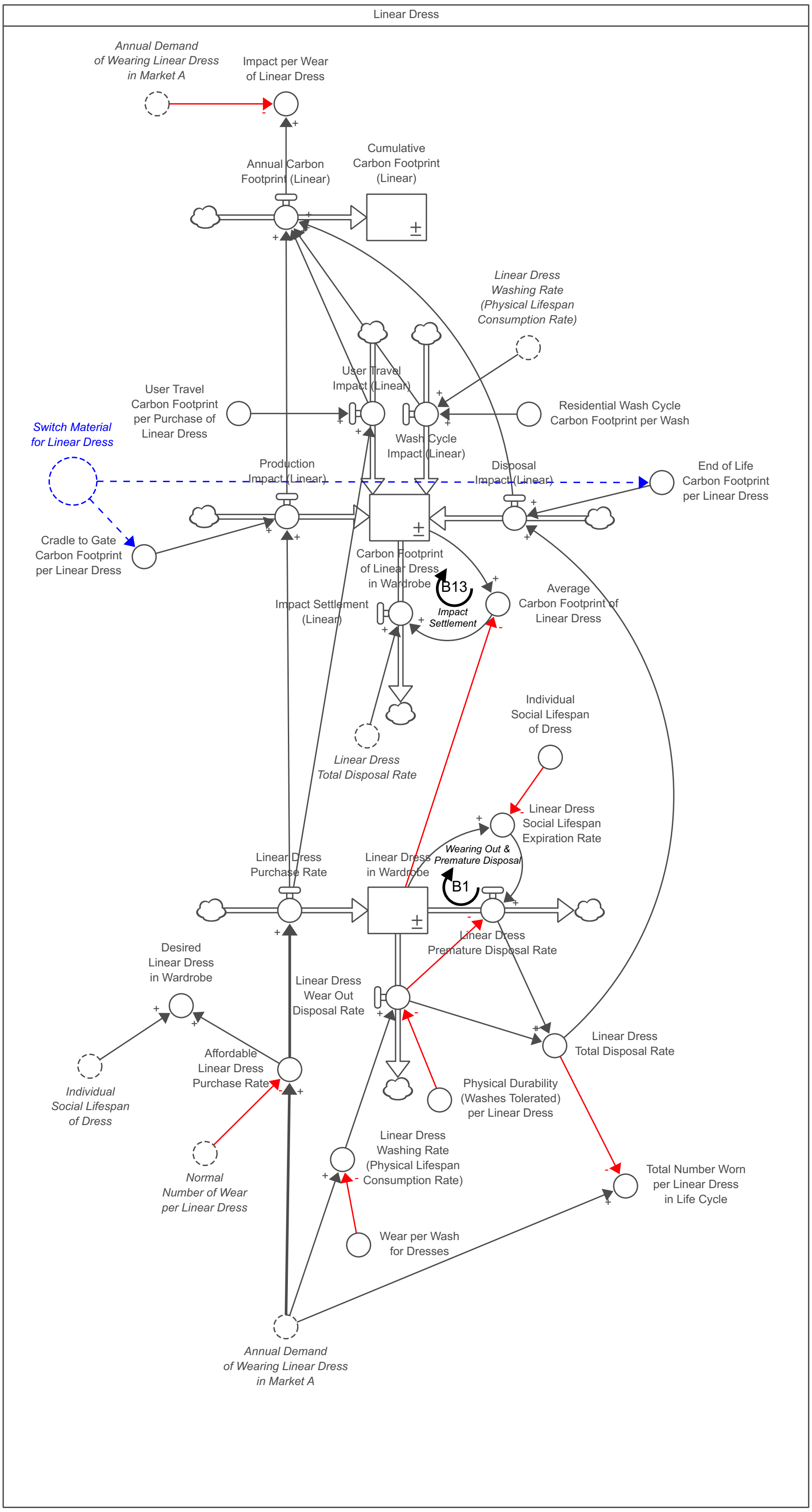

Figure 21 Linear dress module

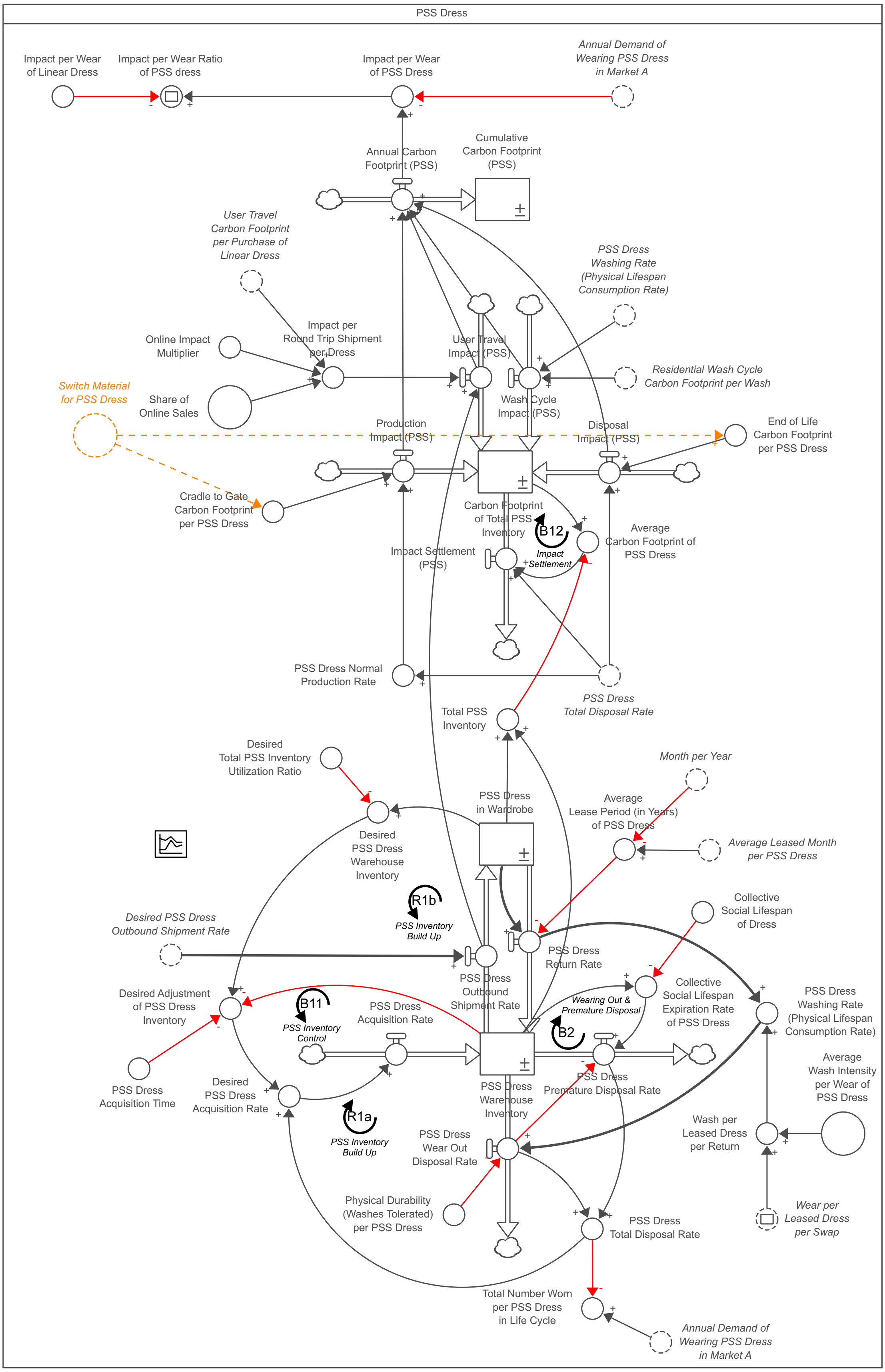

Figure 22 PSS dress module

Appendix.4.3 PSS membership design module

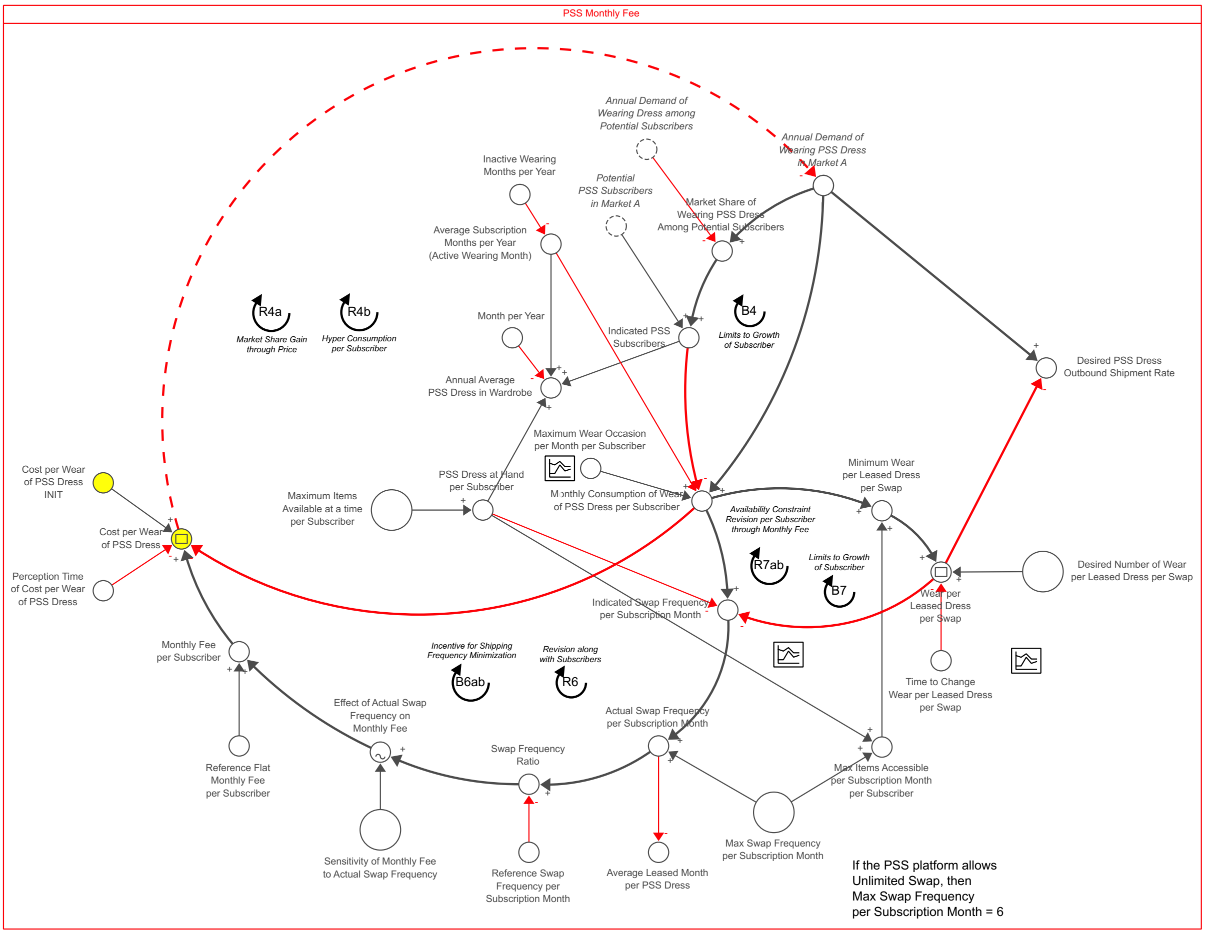

Figure 23 PSS membership design module

Appendix.4.4 Market share module

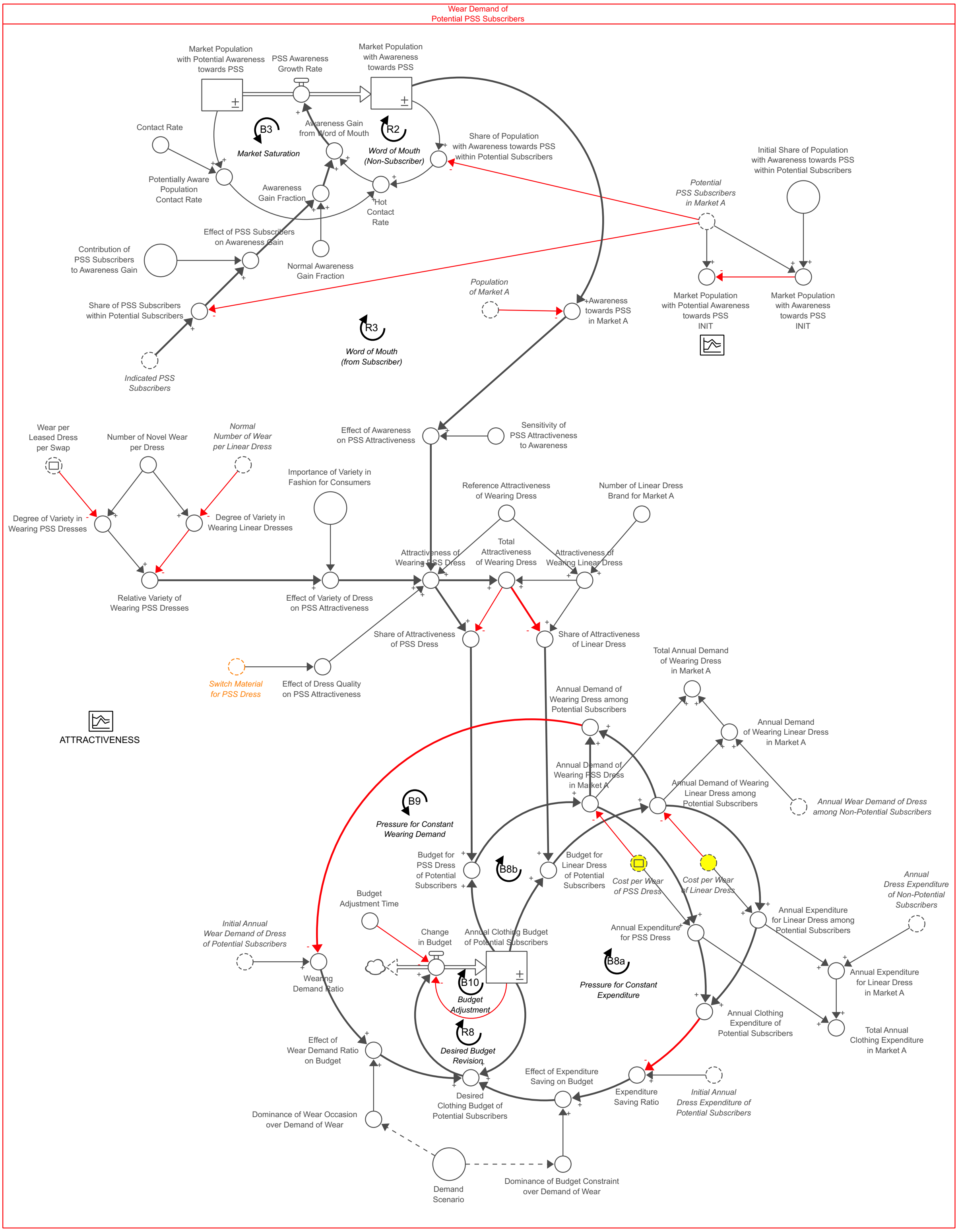

Figure 24 Market share module

Appendix. 5 Scenario Run Parameters

		100% LINEAR DRESS		Introducing PSS Dress							
		Reference Scenario		Unlimited Swap & Flat Fee					Unlimited Swap & VFee		
	Scenario→	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	
	↓Control Variables	Base Run	Ref. Policy	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	Unit
Consumer Variables	Initial Share of Population with Awareness towards PSS within Potential Subscribers	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Unitless
	Demand Scenario (1 = CW, 2 = UM)	1	1	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	Unitless
	Desired Number of Wear per Leased Dress per Swap (WPS)	1	1	1	1	**1**	**2**	**3**	1	3	wear /dress
	Average Fashion Consciousness	0.5	0.5	**0.2**	**0.8**	**0.5**	**0.5**	**0.5**	0.5	0.5	Unitless
Retailers/ Platform Variables	Switch Material for Linear Dress	0	1	0	0	0	0	0	0	0	Unitless
	Switch Material for PSS Dress	0	0	0	0	0	0	0	0	0	Unitless
	Sensitivity of Monthly Fee to Actual Swap Frequency	**0**	**0**	**0**	**0**	**0**	**0**	**0**	1	1	Unitless
	Maximum Items Available at a time per Subscriber	3	3	3	3	3	3	3	3	3	dress /person
	Max Swap Frequency per Subscription Month	6	6	6	6	6	6	6	6	6	1/month
	Reference Flat Monthly Fee per Subscriber	60	60	60	60	60	60	60	60	60	EUR/month /person
	Average Wash Intensity per Wear of PSS Dress	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	care cycle /wear
	Contribution of PSS Subscribers to Awareness Gain	1	1	1	1	1	1	1	1	1	Unitless
						↑Vulnerable Membership Design					
									c.f. Run 5	c.f. Run 7	

		Introducing PSS Dress											
		Limited Swap & VFee				VAT Reduction		Lifespan Degradation			+PSS Attractiveness		
	Scenario→	Run 10	Run 11	Run 12	Run 13 *	Run 14	Run 15	Run 16	Run 17	Run 18	Run 19	Run 20	
	↓Control Variables	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	CW&UM	Unit
Consumer Variables	Initial Share of Population with Awareness towards PSS within Potential Subscribers	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Unitless
	Demand Scenario (1 = CW, 2 = UM)	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2	Unitless
	Desired Number of Wear per Leased Dress per Swap (WPS)	1	3	1	1	1	1	**1**	**2**	**3**	1	1	wear /dress
	Average Fashion Consciousness	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Unitless
Retailers/ Platform Variables	Switch Material for Linear Dress	0	0	0	0	0	0	0	0	0	0	0	Unitless
	Switch Material for PSS Dress	0	0	0	0	0	0	0	0	0	0	**2**	Unitless
	Sensitivity of Monthly Fee to Actual Swap Frequency	1	1	1	1	**0**	1	**0**	**0**	**0**	1	1	Unitless
	Maximum Items Available at a time per Subscriber	3	3	**5**	3	3	3	3	3	3	3	3	dress /person
	Max Swap Frequency per Subscription Month	2	2	2	2	6	2	6	6	6	2	2	1/month
	Reference Flat Monthly Fee per Subscriber	60	60	60	60	**51**	**51**	60	60	60	60	60	EUR/month /person
	Average Wash Intensity per Wear of PSS Dress	0.33	0.33	0.33	0.33	0.33	0.33	**1**	**1**	**1**	0.33	0.33	care cycle /wear
	Contribution of PSS Subscribers to Awareness Gain	1	1	1	1	1	1	1	1	1	**0**	1	Unitless
		↑ Robust Membership Design ↑											
		c.f. Run 5	c.f. Run 7	c.f. Run 10	c.f. Run 10	c.f. Run 5	c.f. Run 10	c.f. Run 5	c.f. Run 6	c.f. Run 7	c.f. Run 10	c.f. Run 10	

*Initial Annual Wear Occasion of Dress per Person = 25 wear/year/person instead of 50 wear/year/person
Initial Linear Dress Purchase Rate per Person = 2.5 dress/year/person instead of 5 dress/year/person

Table 4 Scenario run parameters

Appendix. 6 Supplementary Simulation Results

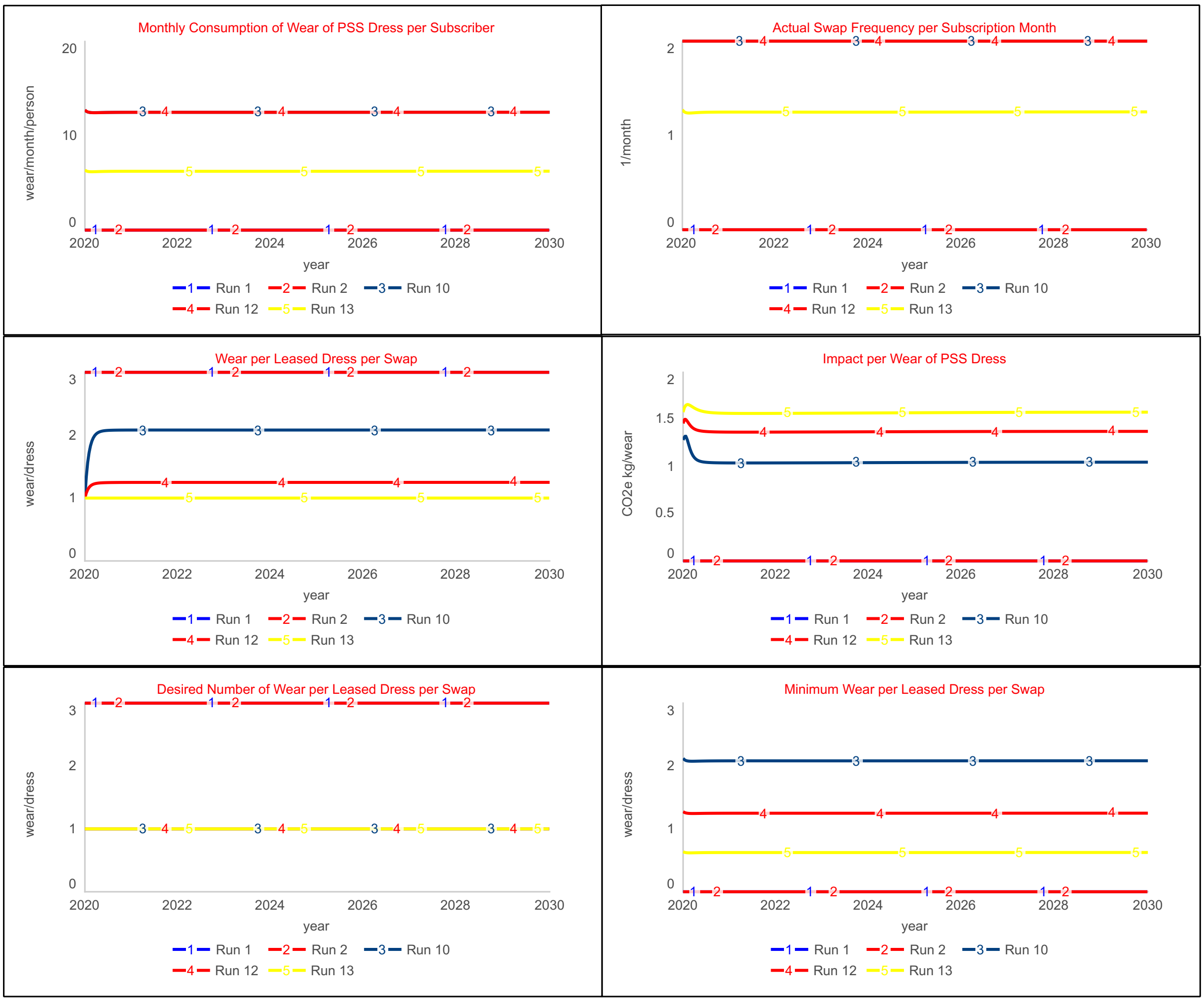

Figure 25 Cases when limited max swaps & max item at hand cannot raise WPS

By technically limiting the availability of dresses accessible per month (Loop R7ab), it induces the minimum WPS to increase above one wear to satisfy the monthly demand of wear (i.e. the minimum WPS increases more than one), even if the users originally wanted to wear different dresses every time (Run 10). At the same time, it is necessary that the maximum item at a time is also small enough (e.g. three items at a time in Run 10) to increase the minimum WPS meaningfully, and if it is large (e.g. five items at a time in Run 12), it would still allow WPS of close to one for a monthly demand of 12.5 wear/month/person. It also needs that the monthly demand is sufficiently large, since if the monthly demand is small (e.g. 6.25 wear/month/person in Run 13), the minimum WPS stays lower than one and hence the actual WPS remains at the desired number of one wear.

Appendix. 7 Simulation Model Documentation

Variable Name	Equation	Properties	Units	Documentation
Annual_Clothing_Budget_of_Potential_Subscribers(t)	Annual_Clothing_Budget_of_Potential_Subscribers(t - dt) + (Change_in_Budget) * dt	INIT Annual_Clothing_Budget_of_Potential_Subscribers = Initial_Annual_Dress_Expenditure_of_Potential_Subscribers	EUR/year	
Carbon_Footprint_of_Linear_Dress_in_Wardrobe(t)	Carbon_Footprint_of_Linear_Dress_in_Wardrobe(t - dt) + ("Production_Impact_(Linear)" + "Wash_Cycle_Impact_(Linear)" + "User_Travel_Impact_(Linear)" + "Disposal_Impact_(Linear)" - "Impact_Settlement_(Linear)") * dt	INIT Carbon_Footprint_of_Linear_Dress_in_Wardrobe = Linear_Dress_in_Wardrobe* (Cradle_to_Gate_Carbon_Footprint_per_Linear_Dress+User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress+End_of_Life_Carbon_Footprint_per_Linear_Dress+(Total_Number_Worn_per_Linear_Dress_in_Life_Cycle/Wear_per_Wash_for_Dresses*Residential_Wash_Cycle_Carbon_Footprint_per_Wash))	CO2e kg	Adjustment to Default Impact per Dress (18 CO2e kg/Dress) applied to 1) Wash cycle impact (since actual number worn can be different from reference dress) 2) Production Impact (since material choice can influence impact per production)
Carbon_Footprint_of_Stock_of_Dress_in_Market_A(t)	Carbon_Footprint_of_Stock_of_Dress_in_Market_A(t - dt) + ("Production_Impact_(Market_A)" + "Wash_Cycle_Impact_(Market_A)" + "User_Travel_Impact_(Market_A)" + "Disposal_Impact_(Market_A)" - "Impact_Settlement_(Market_A)") * dt	INIT Carbon_Footprint_of_Stock_of_Dress_in_Market_A = Carbon_Footprint_of_Linear_Dress_in_Wardrobe+Carbon_Footprint_of_Total_PSS_Inventory	CO2e kg	
Carbon_Footprint_of_Total_PSS_Inventory(t)	Carbon_Footprint_of_Total_PSS_Inventory(t - dt) + ("Production_Impact_(PSS)" + "Wash_Cycle_Impact_(PSS)" + "User_Travel_Impact_(PSS)" + "Disposal_Impact_(PSS)" - "Impact_Settlement_(PSS)") * dt	INIT Carbon_Footprint_of_Total_PSS_Inventory = Total_PSS_Inventory* (Cradle_to_Gate_Carbon_Footprint_per_PSS_Dress+Lifetime_Transportation_Impact_per_PSS_Dress_Produced+End_of_Life_Carbon_Footprint_per_PSS_Dress+ (Total_Number_Worn_per_PSS_Dress_in_Life_Cycle/Wear_per_Wash_for_Dresses*Residential_Wash_Cycle_Carbon_Footprint_per_Wash))	CO2e kg	
"Cumulative_Carbon_Footprint_(Linear)"(t)	"Cumulative_Carbon_Footprint_(Linear)"(t - dt) + ("Annual_Carbon_Footprint_(Linear)") * dt	INIT "Cumulative_Carbon_Footprint_(Linear)" = 0	CO2e kg	
"Cumulative_Carbon_Footprint_(PSS)"(t)	"Cumulative_Carbon_Footprint_(PSS)"(t - dt) + ("Annual_Carbon_Footprint_(PSS)") * dt	INIT "Cumulative_Carbon_Footprint_(PSS)" = 0	CO2e kg	
Linear_Dress_in_Wardrobe(t)	Linear_Dress_in_Wardrobe(t - dt) + (Linear_Dress_Purchase_Rate - Linear_Dress_Premature_Disposal_Rate - Linear_Dress_Wear_Out_Disposal_Rate) * dt	INIT Linear_Dress_in_Wardrobe = Desired_Linear_Dress_in_Wardrobe	dress	
Market_A_Cumulative_Revenue_of_Linear_Dress(t)	Market_A_Cumulative_Revenue_of_Linear_Dress(t - dt) + (Linear_Dress_Revenue) * dt	INIT Market_A_Cumulative_Revenue_of_Linear_Dress = 0	EUR	
Market_A_Cumulative_Revenue_of_PSS_Dress(t)	Market_A_Cumulative_Revenue_of_PSS_Dress(t - dt) + (PSS_Dress_Revenue) * dt	INIT Market_A_Cumulative_Revenue_of_PSS_Dress = 0	EUR	
Market_A_Total_Cumulative_Carbon_Footprint(t)	Market_A_Total_Cumulative_Carbon_Footprint(t - dt) + (Market_A_Total_Annual_Carbon_Footprint) * dt	INIT Market_A_Total_Cumulative_Carbon_Footprint = 0	CO2e kg	
Market_A_Total_Cumulative_Revenue_of_Dress(t)	Market_A_Total_Cumulative_Revenue_of_Dress(t - dt) + (Total_Dress_Revenue) * dt	INIT Market_A_Total_Cumulative_Revenue_of_Dress = 0	EUR	
Market_Population_with_Awareness_towards_PSS(t)	Market_Population_with_Awareness_towards_PSS(t - dt) + (PSS_Awareness_Growth_Rate) * dt	INIT Market_Population_with_Awareness_towards_PSS = Market_Population_with_Awareness_towards_PSS_INIT	person	
Market_Population_with_Potential_Awareness_towards_PSS(t)	Market_Population_with_Potential_Awareness_towards_PSS(t - dt) + (- PSS_Awareness_Growth_Rate) * dt	INIT Market_Population_with_Potential_Awareness_towards_PSS = Market_Population_with_Potential_Awareness_towards_PSS_INIT	person	
PSS_Dress_in_Wardrobe(t)	PSS_Dress_in_Wardrobe(t - dt) + (PSS_Dress_Outbound_Shipment_Rate - PSS_Dress_Return_Rate) * dt	INIT PSS_Dress_in_Wardrobe = Annual_Average_PSS_Dress_in_Wardrobe	dress	
PSS_Dress_Warehouse_Inventory(t)	PSS_Dress_Warehouse_Inventory(t - dt) + (PSS_Dress_Acquisition_Rate + PSS_Dress_Return_Rate - PSS_Dress_Outbound_Shipment_Rate - PSS_Dress_Premature_Disposal_Rate - PSS_Dress_Wear_Out_Disposal_Rate) * dt	INIT PSS_Dress_Warehouse_Inventory = Desired_PSS_Dress_Warehouse_Inventory	dress	

Variable Name	Equation	Properties	Units	Documentation
Total_Stock_of_Dress_in_Market_A(t)	Total_Stock_of_Dress_in_Market_A(t - dt) + (Total_Dress_Acquisition_Rate - Total_Dress_Premature_Disposal_Rate - Total_Dress_Wear_Out_Disposal_Rate) * dt	INIT Total_Stock_of_Dress_in_Market_A = Linear_Dress_in_Wardrobe+PSS_Dress_in_Wardrobe+PSS_Dress_Warehouse_Inventory	dress	
"Annual_Carbon_Footprint_(Linear)"	"Production_Impact_(Linear)"+"Wash_Cycle_Impact_(Linear)"+"User_Travel_Impact_(Linear)"+"Disposal_Impact_(Linear)"		CO2e kg/year	
"Annual_Carbon_Footprint_(PSS)"	"Production_Impact_(PSS)"+"Wash_Cycle_Impact_(PSS)"+"User_Travel_Impact_(PSS)"+"Disposal_Impact_(PSS)"		CO2e kg/year	
Change_in_Budget	(Desired_Clothing_Budget_of_Potential_Subscribers-Annual_Clothing_Budget_of_Potential_Subscribers)/Budget_Adjustment_Time		EUR/year/year	
"Disposal_Impact_(Linear)"	MAX(0, Linear_Dress_Total_Disposal_Rate*End_of_Life_Carbon_Footprint_per_Linear_Dress)		CO2e kg/year	
"Disposal_Impact_(Market_A)"	"Disposal_Impact_(Linear)"+"Disposal_Impact_(PSS)"		CO2e kg/year	
"Disposal_Impact_(PSS)"	MAX(0, PSS_Dress_Total_Disposal_Rate*End_of_Life_Carbon_Footprint_per_PSS_Dress)		CO2e kg/year	
"Impact_Settlement_(Linear)"	MAX(0,Linear_Dress_Total_Disposal_Rate*Average_Carbon_Footprint_of_Linear_Dress)		CO2e kg/year	
"Impact_Settlement_(Market_A)"	MAX(0,Total_Dress_Disposal_Rate*"Average_Carbon_Footprint_of_Dress_(Market_A)")		CO2e kg/year	
"Impact_Settlement_(PSS)"	MAX(0,PSS_Dress_Total_Disposal_Rate*Average_Carbon_Footprint_of_PSS_Dress)		CO2e kg/year	
Linear_Dress_Premature_Disposal_Rate	MAX(0, Linear_Dress_Social_Lifespan_Expiration_Rate-Linear_Dress_Wear_Out_Disposal_Rate)		dress/year	
Linear_Dress_Purchase_Rate	MAX(0,Affordable_Linear_Dress_Purchase_Rate)		dress/year	
Linear_Dress_Revenue	Linear_Dress_Purchase_Rate*Average_Retail_Price_of_Linear_Dress		EUR/year	
Linear_Dress_Wear_Out_Disposal_Rate	MAX(0,"Linear_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"//"Physical_Durability_(Washes_Tolerated)_per_Linear_Dress")		dress/year	
Market_A_Total_Annual_Carbon_Footprint	"Production_Impact_(Market_A)"+"Wash_Cycle_Impact_(Market_A)"+"User_Travel_Impact_(Market_A)"+"Disposal_Impact_(Market_A)"		CO2e kg/year	
"Production_Impact_(Linear)"	MAX(0, Linear_Dress_Purchase_Rate*Cradle_to_Gate_Carbon_Footprint_per_Linear_Dress)		CO2e kg/year	
"Production_Impact_(Market_A)"	"Production_Impact_(Linear)"+"Production_Impact_(PSS)"		CO2e kg/year	
"Production_Impact_(PSS)"	MAX(0, PSS_Dress_Normal_Production_Rate*Cradle_to_Gate_Carbon_Footprint_per_PSS_Dress)		CO2e kg/year	
PSS_Awareness_Growth_Rate	MAX(0, Awareness_Gain_from_Word_of_Mouth)		person/year	
PSS_Dress_Acquisition_Rate	MAX(0, Desired_PSS_Dress_Acquisition_Rate)		dress/year	
PSS_Dress_Outbound_Shipment_Rate	MAX(0,Desired_PSS_Dress_Outbound_Shipment_Rate)		dress/year	
PSS_Dress_Premature_Disposal_Rate	MAX(0, Collective_Social_Lifespan_Expiration_Rate_of_PSS_Dress-PSS_Dress_Wear_Out_Disposal_Rate)		dress/year	
PSS_Dress_Return_Rate	PSS_Dress_in_Wardrobe//"Average_Lease_Period_(in_Years)_of_PSS_Dress"		dress/year	
PSS_Dress_Revenue	"Average_Subscription_Months_per_Year_(Active_Wearing_Month)"*Monthly_Fee_per_Subscriber*Indicated_PSS_Subscribers		EUR/year	
PSS_Dress_Wear_Out_Disposal_Rate	MAX(0,"PSS_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"//"Physical_Durability_(Washes_Tolerated)_per_PSS_Dress")		dress/year	
Total_Dress_Acquisition_Rate	Linear_Dress_Purchase_Rate+PSS_Dress_Acquisition_Rate		dress/year	
Total_Dress_Premature_Disposal_Rate	Linear_Dress_Premature_Disposal_Rate+PSS_Dress_Premature_Disposal_Rate		dress/year	
Total_Dress_Revenue	Linear_Dress_Revenue+PSS_Dress_Revenue		EUR/year	
Total_Dress_Wear_Out_Disposal_Rate	Linear_Dress_Wear_Out_Disposal_Rate+PSS_Dress_Wear_Out_Disposal_Rate		dress/year	

Variable Name	Equation	Properties	Units	Documentation
"User_Travel_Impact_(Linear)"	MAX(0,Linear_Dress_Purchase_Rate*User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress)		CO2e kg/year	
"User_Travel_Impact_(Market_A)"	"User_Travel_Impact_(Linear)"+"User_Travel_Impact_(PSS)"		CO2e kg/year	
"User_Travel_Impact_(PSS)"	MAX(0,Impact_per_Round_Trip_Shipment_per_Dress*PSS_Dress_Outbound_Shipment_Rate)		CO2e kg/year	
"Wash_Cycle_Impact_(Linear)"	MAX(0, "Linear_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"*Residential_Wash_Cycle_Carbon_Footprint_per_Wash)		CO2e kg/year	
"Wash_Cycle_Impact_(Market_A)"	"Wash_Cycle_Impact_(Linear)"+"Wash_Cycle_Impact_(PSS)"		CO2e kg/year	
"Wash_Cycle_Impact_(PSS)"	MAX(0, "PSS_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"*Residential_Wash_Cycle_Carbon_Footprint_per_Wash)		CO2e kg/year	
Actual_Leverage_of_Clothing_Utilization_by_PSS	Total_Number_Worn_per_PSS_Dress_in_Life_Cycle//Total_Number_Worn_per_Linear_Dress_in_Life_Cycle		Dimensionless	
Actual_Swap_Frequency_per_Subscription_Month	MIN(Max_Swap_Frequency_per_Subscription_Month, Indicated_Swap_Frequency_per_Subscription_Month)		1/month	
Affordable_Linear_Dress_Purchase_Rate	Annual_Demand_of_Wearing_Linear_Dress_in_Market_A//Normal_Number_of_Wear_per_Linear_Dress		dress/year	
Annual_Average_PSS_Dress_in_Wardrobe	PSS_Dress_at_Hand_per_Subscriber*Indicated_PSS_Subscribers*"Average_Subscription_Months_per_Year_(Active_Wearing_Month)"//Month_per_Year		dress	
Annual_Clothing_Expenditure_of_Potential_Subscribers	Annual_Expenditure_for_PSS_Dress+Annual_Expenditure_for_Linear_Dress_among_Potential_Subscribers		EUR/year	
Annual_Demand_of_Wearing_Dress_among_Potential_Subscribers	Annual_Demand_of_Wearing_PSS_Dress_in_Market_A+Annual_Demand_of_Wearing_Linear_Dress_among_Potential_Subscribers		wear/year	
Annual_Demand_of_Wearing_Linear_Dress_among_Potential_Subscribers	Budget_for_Linear_Dress_of_Potential_Subscribers//Cost_per_Wear_of_Linear_Dress		wear/year	
Annual_Demand_of_Wearing_Linear_Dress_in_Market_A	"Annual_Wear_Demand_of_Dress_among_Non-Potential_Subscribers"+Annual_Demand_of_Wearing_Linear_Dress_among_Potential_Subscribers		wear/year	
Annual_Demand_of_Wearing_PSS_Dress_in_Market_A	Budget_for_PSS_Dress_of_Potential_Subscribers//Cost_per_Wear_of_PSS_Dress		wear/year	
"Annual_Dress_Expenditure_of_Non-Potential_Subscribers"	"Initial_Annual_Dress_Expenditure_per_Person_(who_buy_dress)"*"Non-Potential_PSS_Subscribers_in_Market_A"		EUR/year	
Annual_Expenditure_for_Linear_Dress_among_Potential_Subscribers	Annual_Demand_of_Wearing_Linear_Dress_among_Potential_Subscribers*Cost_per_Wear_of_Linear_Dress		EUR/year	
Annual_Expenditure_for_Linear_Dress_in_Market_A	"Annual_Dress_Expenditure_of_Non-Potential_Subscribers"+Annual_Expenditure_for_Linear_Dress_among_Potential_Subscribers		EUR/year	
Annual_Expenditure_for_PSS_Dress	Annual_Demand_of_Wearing_PSS_Dress_in_Market_A*Cost_per_Wear_of_PSS_Dress		EUR/year	
"Annual_Wear_Demand_of_Dress_among_Non-Potential_Subscribers"	"Initial_Annual_Wear_Occasion_of_Dress_per_Person_(who_buy_dress)"*"Non-Potential_PSS_Subscribers_in_Market_A"		wear/year	
Attractiveness_of_Wearing_Linear_Dress	Reference_Attractiveness_of_Wearing_Dress*Number_of_Linear_Dress_Brand_for_Market_A		Dimensionless	
Attractiveness_of_Wearing_PSS_Dress	Reference_Attractiveness_of_Wearing_Dress*Effect_of_Variety_of_Dress_on_PSS_Attractiveness*Effect_of_Awareness_on_PSS_Attractiveness*Effect_of_Dress_Quality_on_PSS_Attractiveness		Dimensionless	

Variable Name	Equation	Properties	Units	Documentation
"Average_Carbon_Footprint_of_Dress_(Market_A)"	Carbon_Footprint_of_Stock_of_Dress_in_Market_A//Total_Stock_of_Dress_in_Market_A		CO2e kg/dress	
Average_Carbon_Footprint_of_Linear_Dress	Carbon_Footprint_of_Linear_Dress_in_Wardrobe//Linear_Dress_in_Wardrobe		CO2e kg/dress	
Average_Carbon_Footprint_of_PSS_Dress	Carbon_Footprint_of_Total_PSS_Inventory//Total_PSS_Inventory		CO2e kg/dress	
Average_Factor_of_Lifetime_Users_per_PSS_Dress	Total_Number_Worn_per_PSS_Dress_in_Life_Cycle//Wear_per_Leased_Dress_per_Swap		Dimensionless	
Average_Fashion_Consciousness	0.5		Dimensionless	
"Average_Lease_Period_(in_Years)_of_PSS_Dress"	Average_Leased_Month_per_PSS_Dress/Month_per_Year		year	
Average_Leased_Month_per_PSS_Dress	1//Actual_Swap_Frequency_per_Subscription_Month		month	
Average_Retail_Price_of_Linear_Dress	60		EUR/dress	Assuming a regular dress used for daily wear.
"Average_Subscription_Months_per_Year_(Active_Wearing_Month)"	12-Inactive_Wearing_Months_per_Year		month/year	
Average_Wash_Intensity_per_Wear_of_PSS_Dress	1/3		care cycle/wear	A value that can range from 1/3 to 1. The rate of 1/3 corresponds to the same wash per wear of a linear dress. To realize this value, a platform has to be 3 times more efficient and less impacting to cause wash cycle impact and physical degradation of a dress, even though a user wears for one full occasion. It also requires that a user wears in such a way that the degree of contamination will be 1/3 compared to when wearing the same dress for 3 times.
Awareness_Gain_Fraction	Normal_Awareness_Gain_Fraction*Effect_of_PSS_Subscribers_on_Awareness_Gain		Dimensionless	
Awareness_Gain_from_Word_of_Mouth	Hot_Contact_Rate*Awareness_Gain_Fraction		person/year	Also can be formulated as: Potential_Adopters_of_CFC*Contact_Rate*(Adopters_of_CFC/Total_Market_Population)*Adoption_Fraction
Awareness_towards_PSS_in_Market_A	Market_Population_with_Awareness_towards_PSS//Population_of_Market_A		Dimensionless	
Budget_Adjustment_Time	1/12		year	
Budget_for_Linear_Dress_of_Potential_Subscribers	Annual_Clothing_Budget_of_Potential_Subscribers*Share_of_Attractiveness_of_Linear_Dress		EUR/year	
Budget_for_PSS_Dress_of_Potential_Subscribers	Annual_Clothing_Budget_of_Potential_Subscribers*Share_of_Attractiveness_of_PSS_Dress		EUR/year	
Collective_Social_Lifespan_Expiration_Rate_of_PSS_Dress	PSS_Dress_Warehouse_Inventory//Collective_Social_Lifespan_of_Dress		dress/year	
Collective_Social_Lifespan_of_Dress	4		year	
Contact_Rate	12		person/person/year	
Contribution_of_PSS_Subscribers_to_Awareness_Gain	1		Dimensionless	
Cost_per_Wear_of_Linear_Dress	Average_Retail_Price_of_Linear_Dress//Normal_Number_of_Wear_per_Linear_Dress		EUR/wear	6+STEP(1, 2027)*0

Variable Name	Equation	Properties	Units	Documentation
Cost_per_Wear_of_PSS_Dress	SMTH1(Monthly_Fee_per_Subscriber//Monthly_Consumption_of_Wear_of_PSS_Dress_per_Subscriber, Perception_Time_of_Cost_per_Wear_of_PSS_Dress, Cost_per_Wear_of_PSS_Dress_INIT)		EUR/wear	
Cost_per_Wear_of_PSS_Dress_INIT	IF Market_Population_with_Awareness_towards_PSS_INIT = 0 THEN 0 ELSE 4.8		EUR/wear	
Cost_per_Wear_Ratio_of_PSS_Dress	SMTH1(Cost_per_Wear_of_PSS_Dress//Cost_per_Wear_of_Linear_Dress, Perception_Time_of_Cost_per_Wear_of_PSS_Dress)		Dimensionless	
Cradle_to_Gate_Carbon_Footprint_per_Linear_Dress	IF Switch_Material_for_Linear_Dress = 1 THEN 15*0.93 ELSE IF Switch_Material_for_Linear_Dress = 2 THEN 15*0.93 ELSE 15		CO2e kg/dress	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81) ★Environmental assessment of Swedish clothing consumption—six garments Switch Tencel: Tencel (produced in non-integrated facility, as current benchmark) is assumed to have the same production impact as chemically recycled polyester, since several data exist which shows Tencel has less (Shen et al 2012) or more (Higg MSI) carbon footprint than recycled polyester fiber, while Tencel is indicated to have similar carbon footprint as conventional cotton (Roos et al 2015, Higg MSI). Conventional cotton has less carbon footprint than virgin polyester (Higg MSI, Mistra 2019 Fiber Bibel 2). Replacing all polyester consumption in Sweden would yield 6% of decrease in annual carbon footprint (Roos et al 2016). Hence, it is assumed that replacing virgin polyester to Tencel would yield the same cradle-to-gate impact reduction as switching to chemically recycled polyester (or conventional cotton in terms of carbon footprint). In addition, since Tencel is biodegradable, it can be disposed of in the household compost, resulting in 0 EoL impact.
Cradle_to_Gate_Carbon_Footprint_per_PSS_Dress	IF Switch_Material_for_PSS_Dress = 1 THEN 15*0.93 ELSE IF Switch_Material_for_PSS_Dress = 2 THEN 15*0.93 ELSE 15		CO2e kg/dress	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81) ★Environmental assessment of Swedish clothing consumption—six garments
Degree_of_Variety_in_Wearing_Linear_Dresses	MIN(1, Number_of_Novel_Wear_per_Dress//Normal_Number_of_Wear_per_Linear_Dress)		Dimensionless	
Degree_of_Variety_in_Wearing_PSS_Dresses	MIN(1,Number_of_Novel_Wear_per_Dress//Wear_per_Leased_Dress_per_Swap)		Dimensionless	

Variable Name	Equation	Properties	Units	Documentation
Demand_Scenario	1		Dimensionless	Scenario 1 = Constant Wear Demand and Min Expenditure Scenario 2 = Constant Expenditure and Utility Maximization (Consumption-As-Usual) Scenario 3 = Aiming for both Constant Wear Demand and Constant Expenditure
Desired_Adjustment_of_PSS_Dress_Inventory	(Desired_PSS_Dress_Warehouse_Inventory-PSS_Dress_Warehouse_Inventory)/PSS_Dress_Acquisition_Time		dress/year	
Desired_Clothing_Budget_of_Potential_Subscribers	Annual_Clothing_Budget_of_Potential_Subscribers*Effect_of_Wear_Demand_Ratio_on_Budget*Effect_of_Expenditure_Saving_on_Budget		EUR/year	
Desired_Linear_Dress_in_Wardrobe	Affordable_Linear_Dress_Purchase_Rate*Individual_Social_Lifespan_of_Dress		dress	★Environmental assessment of Swedish clothing consumption—six garments, Sustainable Futures.pdf
Desired_Number_of_Wear_per_Leased_Dress_per_Swap	1		wear/dress	IF SCENARIO = 2 THEN 2 ELSE IF SCENARIO = 5 THEN 2 ELSE 1
Desired_PSS_Dress_Acquisition_Rate	PSS_Dress_Total_Disposal_Rate+Desired_Adjustment_of_PSS_Dress_Inventory		dress/year	
Desired_PSS_Dress_Outbound_Shipment_Rate	Annual_Demand_of_Wearing_PSS_Dress_in_Market_A//Wear_per_Leased_Dress_per_Swap		dress/year	
Desired_PSS_Dress_Warehouse_Inventory	(PSS_Dress_in_Wardrobe/Desired_Total_PSS_Inventory_Utilization_Ratio)*(1-Desired_Total_PSS_Inventory_Utilization_Ratio)		dress	
Desired_Total_PSS_Inventory_Utilization_Ratio	0.7		Dimensionless	
"Disposal_Impact_per_Wear_(Linear)"	Impact_per_Wear_of_Linear_Dress*"Share_of_Disposal_Impact_(Linear)"		CO2e kg/wear	0.69 CO2ekg /wear (Sandin, Roos, Spak, Zamani, & Peters, 2019: 62)
"Disposal_Impact_per_Wear_(PSS)"	Impact_per_Wear_of_PSS_Dress*"Share_of_Disposal_Impact_(PSS)"		CO2e kg/wear	0.69 CO2ekg /wear (Sandin, Roos, Spak, Zamani, & Peters, 2019: 62)
Dominance_of_Budget_Constraint_over_Demand_of_Wear	IF Demand_Scenario = 3 THEN 1 ELSE 0		Dimensionless	
Dominance_of_Wear_Occasion_over_Demand_of_Wear	IF Demand_Scenario = 2 THEN 0 ELSE 1		Dimensionless	
Effect_of_Actual_Swap_Frequency_on_Monthly_Fee	GRAPH(Swap_Frequency_Ratio^Sensitivity_of_Monthly_Fee_to_Actual_Swap_Frequency) Points: (1.000, 1.000), (2.000, 1.500), (3.000, 2.000), (4.000, 2.500), (5.000, 3.000), (6.000, 3.500), (7.000, 4.000), (8.000, 4.500)		Dimensionless	
Effect_of_Awareness_on_PSS_Attractiveness	Awareness_towards_PSS_in_Market_A^Sensitivity_of_PSS_Attractiveness_to_Awareness		Dimensionless	
Effect_of_Dress_Quality_on_PSS_Attractiveness	IF Switch_Material_for_PSS_Dress = 2 THEN 1.1 ELSE 1		Dimensionless	
Effect_of_Expenditure_Saving_on_Budget	Expenditure_Saving_Ratio^Dominance_of_Budget_Constraint_over_Demand_of_Wear		Dimensionless	

Variable Name	Equation	Properties	Units	Documentation
Effect_of_PSS_Subscribers_on_Awareness_Gain	((1+Share_of_PSS_Subscribers_within_Potential_Subscribers)/1)^Contribution_of_PSS_Subscribers_to_Awareness_Gain		Dimensionless	
Effect_of_Variety_of_Dress_on_PSS_Attractiveness	Relative_Variety_of_Wearing_PSS_Dresses^Average_Fashion_Consciousness		Dimensionless	
Effect_of_Wear_Demand_Ratio_on_Budget	Wearing_Demand_Ratio^Dominance_of_Wear_Occasion_over_Demand_of_Wear		Dimensionless	
End_of_Life_Carbon_Footprint_per_Linear_Dress	IF Switch_Material_for_Linear_Dress = 2 THEN 0 ELSE 0.7		CO2e kg/dress	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81)
End_of_Life_Carbon_Footprint_per_PSS_Dress	IF Switch_Material_for_PSS_Dress = 2 THEN 0 ELSE 0.7		CO2e kg/dress	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81)
Expenditure_Saving_Ratio	Initial_Annual_Dress_Expenditure_of_Potential_Subscribers//Annual_Clothing_Expenditure_of_Potential_Subscribers		Dimensionless	
"Fraction_of_Potential_PSS_Subscribers_(Potential_Penetration_Rate)"	0.5		Dimensionless	An arbitrary "penetration rate (i.e. uptake rate)" (Wood et al., 2018:543) of 0.5 is used to distinguish between technically achievable displacement and realistic diffusion of an innovation.
Hot_Contact_Rate	Potentially_Aware_Population_Contact_Rate*Share_of_Population_with_Awareness_towards_PSS_within_Potential_Subscribers		person/year	
I	Cost_per_Wear_of_PSS_Dress		EUR/wear	
Impact_per_Price_Ratio_of_PSS_Dress	Impact_per_Wear_Ratio_of_PSS_dress//Cost_per_Wear_Ratio_of_PSS_Dress		Dimensionless	
Impact_per_Round_Trip_Shipment_per_Dress	Share_of_Online_Sales*User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress*Online_Impact_Multiplier + (1-Share_of_Online_Sales)*User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress		CO2e kg/dress	
"Impact_per_Wear_of_Dress_(Market_A)"	Market_A_Total_Annual_Carbon_Footprint//Total_Annual_Demand_of_Wearing_Dress_in_Market_A		CO2e kg/wear	
Impact_per_Wear_of_Linear_Dress	"Annual_Carbon_Footprint_(Linear)"//Annual_Demand_of_Wearing_Linear_Dress_in_Market_A		CO2e kg/wear	
Impact_per_Wear_of_PSS_Dress	"Annual_Carbon_Footprint_(PSS)"//Annual_Demand_of_Wearing_PSS_Dress_in_Market_A		CO2e kg/wear	
Impact_per_Wear_Ratio_of_PSS_dress	SMTH1(Impact_per_Wear_of_PSS_Dress//Impact_per_Wear_of_Linear_Dress, 1)		Dimensionless	
Inactive_Wearing_Months_per_Year	8		month/year	Consumers are assumed to wear dresses in 4 months in a year (e.g. warm season).
Indicated_PSS_Subscribers	Market_Share_of_Wearing_PSS_Dress_Among_Potential_Subscribers*Potential_PSS_Subscribers_in_Market_A		person	
Indicated_Swap_Frequency_per_Subscription_Month	Monthly_Consumption_of_Wear_of_PSS_Dress_per_Subscriber//Wear_per_Leased_Dress_per_Swap//PSS_Dress_at_Hand_per_Subscriber		1/month	
Individual_Social_Lifespan_of_Dress	3		year	
Initial_Annual_Dress_Expenditure_of_Potential_Subscribers	"Initial_Annual_Dress_Expenditure_per_Person_(who_buy_dress)"*Potential_PSS_Subscribers_in_Market_A		EUR/year	

Variable Name	Equation	Properties	Units	Documentation
"Initial_Annual_Dress_Expenditure_per_Person_(who_buy_dress)"	"Initial_Linear_Dress_Purchase_Rate_per_Person_(who_buy_dress)"*Average_Retail_Price_of_Linear_Dress		EUR/year/person	
Initial_Annual_Wear_Demand_of_Dress_of_Potential_Subscribers	"Initial_Annual_Wear_Occasion_of_Dress_per_Person_(who_buy_dress)"*Potential_PSS_Subscribers_in_Market_A		wear/year	
"Initial_Annual_Wear_Occasion_of_Dress_per_Person_(who_buy_dress)"	50		wear/year/person	Wear per Year for Global Average, derived from (Daystar, Chapman, Moore, Pires, & Golden, 2019) .
Initial_Linear_Dress_Purchase_Rate_of_Potential_Subscribers	"Initial_Linear_Dress_Purchase_Rate_per_Person_(who_buy_dress)"*Potential_PSS_Subscribers_in_Market_A		dress/year	
"Initial_Linear_Dress_Purchase_Rate_per_Person_(who_buy_dress)"	5		dress/year/person	(Roos, Sandin, Zamani, & Peters, 2015:31)
Initial_Share_of_Population_with_Awareness_towards_PSS_within_Potential_Subscribers	0		Dimensionless	
Lifetime_Transportation_Impact_per_PSS_Dress_Produced	User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress*Transportation_Impact_Multiplier_per_Dress_in_PSS_Inventory		CO2e kg/dress	
Linear_Dress_Social_Lifespan_Expiration_Rate	Linear_Dress_in_Wardrobe//Individual_Social_Lifespan_of_Dress		dress/year	
Linear_Dress_Total_Disposal_Rate	Linear_Dress_Wear_Out_Disposal_Rate+Linear_Dress_Premature_Disposal_Rate		dress/year	
"Linear_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"	Annual_Demand_of_Wearing_Linear_Dress_in_Market_A//Wear_per_Wash_for_Dresses		care cycle/year	
Market_Population_with_Awareness_towards_PSS_INIT	Potential_PSS_Subscribers_in_Market_A*Initial_Share_of_Population_with_Awareness_towards_PSS_within_Potential_Subscribers		person	
Market_Population_with_Potential_Awareness_towards_PSS_INIT	Potential_PSS_Subscribers_in_Market_A-Market_Population_with_Awareness_towards_PSS_INIT		person	
Market_Share_of_Wearing_PSS_Dress_Among_Potential_Subscribers	Annual_Demand_of_Wearing_PSS_Dress_in_Market_A//Annual_Demand_of_Wearing_Dress_among_Potential_Subscribers		Dimensionless	
Max_Items_Accessible_per_Subscription_Month_per_Subscriber	PSS_Dress_at_Hand_per_Subscriber*Max_Swap_Frequency_per_Subscription_Month		dress/month/person	
Max_Swap_Frequency_per_Subscription_Month	6		1/month	6 = Unlimited Swap In case of service offering unlimited swaps, it is assumed to result in feasible maximum swap frequency per customer of 6 swaps/month. (one swap per 5 days)
Maximum_Items_Available_at_a_time_per_Subscriber	3		dress/person	
Maximum_Wear_Occasion_per_Month_per_Subscriber	30		wear/month/person	
Minimum_Wear_per_Leased_Dress_per_Swap	Monthly_Consumption_of_Wear_of_PSS_Dress_per_Subscriber//Max_Items_Accessible_per_Subscription_Month_per_Subscriber		wear/dress	
Month_per_Year	12		month/year	

Variable Name	Equation	Properties	Units	Documentation
Monthly_Consumption_of_Wear_of_PSS_Dress_per_Subscriber	MIN(Maximum_Wear_Occasion_per_Month_per_Subscriber, Annual_Demand_of_Wearing_PSS_Dress_in_Market_A/"Average_Subscription_Months_per_Year_(Active_Wearing_Month)"/Indicated_PSS_Subscribers)		wear/month/person	
Monthly_Fee_per_Subscriber	Reference_Flat_Monthly_Fee_per_Subscriber*Effect_of_Actual_Swap_Frequency_on_Monthly_Fee		EUR/month/person	
"Non-Potential_PSS_Subscribers_in_Market_A"	Population_of_Market_A-Potential_PSS_Subscribers_in_Market_A		person	
Normal_Awareness_Gain_Fraction	0.04		Dimensionless	
Normal_Number_of_Wear_per_Linear_Dress	"Initial_Annual_Wear_Occasion_of_Dress_per_Person_(who_buy_dress)"/"Initial_Linear_Dress_Purchase_Rate_per_Person_(who_buy_dress)"		wear/dress	(Zamani et al., 2017:1371)
Number_of_Linear_Dress_Brand_for_Market_A	2		Dimensionless	
Number_of_Novel_Wear_per_Dress	1		wear/dress	IF SCENARIO = 2 THEN 2 ELSE IF SCENARIO = 5 THEN 2 ELSE 1
Online_Impact_Multiplier	0.6		Dimensionless	PEFCR T-shirt p.86 & 87
Perception_Time_of_Cost_per_Wear_of_PSS_Dress	3/12		year	
"Physical_Durability_(Washes_Tolerated)_per_Linear_Dress"	3/30		care cycle/dress	Assuming that a dress can be worn up to 30 times at maximum.
"Physical_Durability_(Washes_Tolerated)_per_PSS_Dress"	3/30		care cycle/dress	Assuming that a dress can be worn up to 30 times at maximum.
"Physical_Durability_(Wears_Tolerated)_per_Retail_Dress"	30		wear/dress	Recycle Polyester or Tencel (R) have the same durability as virgin polyester based dress. IF Switch_Paper_Material = 1 THEN 3*0.1 + 30*(1-0.1) ELSE 30
Population_of_Market_A	10000		person	
Potential_Leverage_of_Clothing_Utilization_of_Retail_Dress	"Physical_Durability_(Wears_Tolerated)_per_Retail_Dress"/Total_Number_Worn_per_Linear_Dress_in_Life_Cycle		Dimensionless	
Potential_PSS_Subscribers_in_Market_A	Population_of_Market_A*"Fraction_of_Potential_PSS_Subscribers_(Potential_Penetration_Rate)"		person	
Potentially_Aware_Population_Contact_Rate	Market_Population_with_Potential_Awareness_towards_PSS*Contact_Rate		person/year	
"Production_Impact_per_Wear_(Linear)"	Impact_per_Wear_of_Linear_Dress*"Share_of_Production_Impact_(Linear)"		CO2e kg/wear	
"Production_Impact_per_Wear_(PSS)"	Impact_per_Wear_of_PSS_Dress*"Share_of_Production_Impact_(PSS)"		CO2e kg/wear	
PSS_Dress_Acquisition_Time	1/12		year	
PSS_Dress_at_Hand_per_Subscriber	Maximum_Items_Available_at_a_time_per_Subscriber		dress/person	
PSS_Dress_Normal_Production_Rate	PSS_Dress_Total_Disposal_Rate*1 + PSS_Dress_Acquisition_Rate*0		dress/year	
PSS_Dress_Total_Disposal_Rate	PSS_Dress_Wear_Out_Disposal_Rate+PSS_Dress_Premature_Disposal_Rate		dress/year	

Variable Name	Equation	Properties	Units	Documentation
"PSS_Dress_Washing_Rate_(Physical_Lifespan_Consumption_Rate)"	PSS_Dress_Return_Rate*Wash_per_Leased_Dress_per_Return		care cycle/year	
Reference_Attractiveness_of_Wearing_Dress	0.5		Dimensionless	
Reference_Flat_Monthly_Fee_per_Subscriber	60		EUR/month/person	
Reference_Swap_Frequency_per_Subscription_Month	1		1/month	
Relative_Variety_of_Wearing_PSS_Dresses	Degree_of_Variety_in_Wearing_PSS_Dresses//Degree_of_Variety_in_Wearing_Linear_Dresses		Dimensionless	
Relative_Weighted_Attractiveness_of_Linear_Dress	Weighted_Attractiveness_of_Linear_Dress//Weighted_Attractiveness_of_PSS_Dress		Dimensionless	
Relative_Weighted_Attractiveness_of_PSS_Dress	Weighted_Attractiveness_of_PSS_Dress//Weighted_Attractiveness_of_Linear_Dress		Dimensionless	
Residential_Wash_Cycle_Carbon_Footprint_per_Wash	0.9/(26/3)		CO2e kg/care cycle	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81) 0.9 CO2e kg (Wash+Dry Impact per dress) / (26 wear (assumed Service Lifespan in the above study) / 3 wear per wash (assumed wash frequency in the above study))
Sensitivity_of_Monthly_Fee_to_Actual_Swap_Frequency	0		Dimensionless	
Sensitivity_of_PSS_Attractiveness_to_Awareness	1		Dimensionless	
Share_of_Attractiveness_of_Linear_Dress	Attractiveness_of_Wearing_Linear_Dress//Total_Attractiveness_of_Wearing_Dress		Dimensionless	
Share_of_Attractiveness_of_PSS_Dress	Attractiveness_of_Wearing_PSS_Dress//Total_Attractiveness_of_Wearing_Dress		Dimensionless	
"Share_of_Disposal_Impact_(Linear)"	"Disposal_Impact_(Linear)"//"Annual_Carbon_Footprint_(Linear)"		Dimensionless	
"Share_of_Disposal_Impact_(PSS)"	"Disposal_Impact_(PSS)"//"Annual_Carbon_Footprint_(PSS)"		Dimensionless	
Share_of_Online_Sales	1		Dimensionless	
Share_of_Population_with_Awareness_towards_PSS_within_Potential_Subscribers	Market_Population_with_Awareness_towards_PSS//Potential_PSS_Subscribers_in_Market_A		Dimensionless	
"Share_of_Production_Impact_(Linear)"	"Production_Impact_(Linear)"//"Annual_Carbon_Footprint_(Linear)"		Dimensionless	
"Share_of_Production_Impact_(PSS)"	"Production_Impact_(PSS)"//"Annual_Carbon_Footprint_(PSS)"		Dimensionless	
Share_of_PSS_Subscribers_within_Potential_Subscribers	Indicated_PSS_Subscribers//Potential_PSS_Subscribers_in_Market_A		Dimensionless	
"Share_of_User_Travel_Impact_(Linear)"	"User_Travel_Impact_(Linear)"//"Annual_Carbon_Footprint_(Linear)"		Dimensionless	
"Share_of_User_Travel_Impact_(PSS)"	"User_Travel_Impact_(PSS)"//"Annual_Carbon_Footprint_(PSS)"		Dimensionless	
"Share_of_Wash_Cycle_Impact_(Linear)"	"Wash_Cycle_Impact_(Linear)"//"Annual_Carbon_Footprint_(Linear)"		Dimensionless	
"Share_of_Wash_Cycle_Impact_(PSS)"	"Wash_Cycle_Impact_(PSS)"//"Annual_Carbon_Footprint_(PSS)"		Dimensionless	
Swap_Frequency_Ratio	Actual_Swap_Frequency_per_Subscription_Month//Reference_Swap_Frequency_per_Subscription_Month		Dimensionless	
Switch_Material_for_Linear_Dress	0		Dimensionless	1 = Recycled Polyester 2 = Tencel

Variable Name	Equation	Properties	Units	Documentation
Switch_Material_for_PSS_Dress	0		Dimensionless	
Time_to_Change_Wear_per_Leased_Dress_per_Swap	1/12		year	
Total_Annual_Clothing_Expenditure_in_Market_A	Annual_Expenditure_for_Linear_Dress_in_Market_A+Annual_Expenditure_for_PSS_Dress		EUR/year	
Total_Annual_Demand_of_Wearing_Dress_in_Market_A	Annual_Demand_of_Wearing_Linear_Dress_in_Market_A+Annual_Demand_of_Wearing_PSS_Dress_in_Market_A		wear/year	
Total_Attractiveness_of_Wearing_Dress	Attractiveness_of_Wearing_PSS_Dress+Attractiveness_of_Wearing_Linear_Dress		Dimensionless	
Total_Dress_Disposal_Rate	Total_Dress_Wear_Out_Disposal_Rate+Total_Dress_Premature_Disposal_Rate		dress/year	
Total_Number_Worn_per_Linear_Dress_in_Life_Cycle	Annual_Demand_of_Wearing_Linear_Dress_in_Market_A//Linear_Dress_Total_Disposal_Rate		wear/dress	
Total_Number_Worn_per_PSS_Dress_in_Life_Cycle	Annual_Demand_of_Wearing_PSS_Dress_in_Market_A//PSS_Dress_Total_Disposal_Rate		wear/dress	
Total_PSS_Inventory	PSS_Dress_Warehouse_Inventory+PSS_Dress_in_Wardrobe		dress	
Total_Weighted_Attractiveness_of_Dress	Weighted_Attractiveness_of_PSS_Dress+Weighted_Attractiveness_of_Linear_Dress		wear/EUR	
Transportation_Impact_Multiplier_per_Dress_in_PSS_Inventory	Share_of_Online_Sales* Average_Factor_of_Lifetime_Users_per_PSS_Dress*Online_Impact_Multiplier + (1-Share_of_Online_Sales)* Average_Factor_of_Lifetime_Users_per_PSS_Dress		Dimensionless	
User_Travel_Carbon_Footprint_per_Purchase_of_Linear_Dress	1.7		CO2e kg/dress	(Sandin, Roos, Spak, Zamani, & Peters, 2019: 81) Reference Impact per Shipment (Retail Consumer Travel Carbon Footprint per Dress for Round Trip, in store sales) = 17km of round trip, 50% car and 50% public transport, for "in-store" sales.
"User_Travel_Impact_per_Wear_(Linear)"	Impact_per_Wear_of_Linear_Dress*"Share_of_User_Travel_Impact_(Linear)"		CO2e kg/wear	
"User_Travel_Impact_per_Wear_(PSS)"	Impact_per_Wear_of_PSS_Dress*"Share_of_User_Travel_Impact_(PSS)"		CO2e kg/wear	
"Wash_Cycle_Impact_per_Wear_(Linear)"	Impact_per_Wear_of_Linear_Dress*"Share_of_Wash_Cycle_Impact_(Linear)"		CO2e kg/wear	
"Wash_Cycle_Impact_per_Wear_(PSS)"	"Share_of_Wash_Cycle_Impact_(PSS)"*Impact_per_Wear_of_PSS_Dress		CO2e kg/wear	
Wash_per_Leased_Dress_per_Return	MAX(1/3,MIN(1, Wear_per_Leased_Dress_per_Swap*Average_Wash_Intensity_per_Wear_of_PSS_Dress))		care cycle/dress	
Wear_per_Leased_Dress_per_Swap	SMTH1(MAX(Desired_Number_of_Wear_per_Leased_Dress_per_Swap,Minimum_Wear_per_Leased_Dress_per_Swap),Time_to_Change_		wear/dress	

Variable Name	Equation	Properties	Units	Documentation
Wear_per_Wash_for_Dresses	3		wear/care cycle	(Zamani et al., 2017:1371)
Wearing_Demand_Ratio	Initial_Annual_Wear_Demand_of_Dress_of_Potential_Subscribers//Annual_Demand_of_Wearing_Dress_among_Potential_Subscribers		Dimensionless	
Weighted_Attractiveness_of_Linear_Dress	Attractiveness_of_Wearing_Linear_Dress//Cost_per_Wear_of_Linear_Dress		wear/EUR	
Weighted_Attractiveness_of_PSS_Dress	Attractiveness_of_Wearing_PSS_Dress//Cost_per_Wear_of_PSS_Dress		wear/EUR	

Total	Count	Including Array Elements
Variables	219	219
Sectors	6	
Stocks	16	16
Flows	34	34
Converters	169	169
Constants	42	42
Equations	161	161
Graphicals	1	1
Macro Variables	20	
Run Specs		
Start Time	2020	
Stop Time	2030	
DT	0.01	
Fractional DT	FALSE	
Save Interval	0.01	
Sim Duration	0	
Time Units	year	
Pause Interval	0	
Integration Method	RK4	
Track flow quantities	TRUE	
Keep all variable results	TRUE	
Run By	Run	
Calculate loop dominance information	FALSE	

Table 5 Simulation model documentation