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Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles

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Abstract

The implementation of circular economy (CE) thinking to reduce environmental impacts and resource use has led to the development of innovative recycling technologies and business models. The implications of these technologies and models, however, remain largely unclear. In many CE strategies, there is a high risk of rebound, meaning a situation in which activities aimed at environmental benefits are not realized because of external reasons. A similar risk relates to limited understanding about the behavioral changes required by extensive implementation of circular practices. Using life cycle assessment, we compare the global warming potential (GWP) of five ownership and end-of-life scenarios for creating and using a pair of jeans. The scenarios are as follows: (a) BASE, i.e. basic use with waste disposal; (b) REDUCE, i.e. extended use; (c) REUSE, i.e. re-selling; (d) RECYCLE, i.e. industrial processing into new raw materials; and (e) SHARE, i.e. a rental service. Our results show that the lowest global warming impacts are achieved in the REDUCE scenario, and the second lowest are achieved in the REUSE scenario. The RECYCLE scenario leads to relatively high overall emissions because the replaced emissions from cotton production are relatively low. The use of rental services is likely to increase customers' mobility, and if that happens in a large scale, then the SHARE scenario has the highest GWP. It was found that many new CE innovations come with a high rebound risk, and existing practices carry similar, yet smaller risks.

1. Introduction

Circular economy (CE) is a concept according to which waste can be designed out of an economy through continuous circulation of products and materials (Ellen MacArthur Foundation 2017, Murray *et al* 2017). There is an ongoing debate about the central features of CE (Urbinati *et al* 2017, Lüdeke-Freund *et al* 2019, Centobelli *et al* 2020), but typically, they are considered to relate to the '3R principles' of reduction, reuse, and recycling (Ghisellini *et al* 2016). These principles can be operationalized in context specific ways, for example through increased sharing of resources (Stahel 2016). The basic argument for CE is that transition to practices that support the principles of CE is expected to reduce environmental burden compared to existing practices, which often are seen as maintaining the current, linear economic model (Geissdoerfer *et al* 2017). In reality, however, we have a limited understanding of the lifecycle impacts of CE practices compared to those of the linear economy (Kirchherr *et al* 2017, Millar *et al* 2019).

Planetary boundaries is a concept describing nine environmental thresholds that define a safe operational space for human activities (Steffen *et al* 2015). Because in many operational areas human activities are exceeding planetary boundaries, there is a well-justified and urgent need to reduce the environmental burden through increased implementation of CE-related practices in societal planning and business development. At the same time, there is a significant risk that intensifying the circulation of materials and products in certain parts of the value chain could lead to unexpected outcomes at the system level, which can be harmful not only to the environment but also to society at large (Pfaff and Sartorius 2015, Korhonen *et al* 2018). For example, the use of recycled plastics in the production of new plastics may require higher total energy consumption than when virgin materials are used (Huysveld *et al* 2019).

Recent studies have provided contradictory evidence regarding the effects of CE-related practices. In some cases, closing material and product loops seem to decrease primary production, thus decreasing the total environmental burden. This happens, for example, when captured CO_2 is transformed into new products or raw materials (Levänen and Eloneva 2017). In other situations, however, similar activities may reverse environmental benefits (Zink and Geyer 2017). For example, increased recycling of textiles does not decrease the overall environmental burden of the sector if textiles' production and consumption continues to grow (Koligkioni *et al* 2018).

The rebound effect is a well-known phenomenon in which resource efficiency gains, caused by a new technology or organizational practice, are not achieved or they remain smaller than expected for external reasons (Grepperud and Rasmussen 2004, Hertwich 2005, Ottelin *et al* 2020). As the principles of CE are directly related to more efficient utilization of resources, the rebound effect requires extra attention in the CE context (Figge and Thorpe 2019). In this article, we compare global warming potential (GWP) of existing CE practices and new CE innovations. By focusing on the different ownership and end-of-life scenarios for a pair of jeans, we demonstrate to role of rebound effect and the meaning of behavioral changes in the advancement of CE. By pinpointing the role of the rebound effect in the studied scenarios, our research identifies specific areas where behavioral changes need to take place to decrease GWP impact of clothing. This specifies current understanding about the importance of behavioral changes in the context of sustainability improvements in the textile sector (Zamami *et al* 2017, Piontek and Müller 2018, Piontek *et al* 2020).

The article is structured as follows. In the next section, we describe our methodology, the data, and the analyzed scenarios. In the third section, we present the results of the life cycle inventory analysis. In the fourth section, we discuss our results and conclude with a reflection on the roles of the rebound effect and behavioral changes in CE contexts.

2. Materials and methods

To compare existing and new CE practices in the textile sector, we perform life cycle assessment (LCA). The geographical focus of our analysis is the European Union (EU), but our findings are informative for countries across the world. The developed LCA model is based on the general guidelines of the ISO 2006 and ISO 2006 standards and was created using the GaBi 9.2 LCA software and databases (GaBi 2019. Thinkstep AG, ISO 14040. EN ISO 14040:2006, ISO 14044. EN ISO 14044:2006, ISO 14049. ISO/TR 14049:2000). The model was complemented with additional data from the literature.

Our focus on GWP impacts has left implications for other important sustainability dimensions—such as water use, toxic chemicals and waste generation (see Allwood *et al* 2008, Roos *et al* 2016)—outside the scope of this study. This analytical choice, however, has allowed us to make more specific comparisons between the studied scenarios than what could be possible with multiple dimensions.

2.1. The goal and scope definition

The current fast fashion paradigm manifests linear economy thinking. According to estimates, up to 6%–10% of global greenhouse gas emissions originate from the textile industry (Quantis 2018, Niinimäki *et al* 2020). Examining the state of the industry in 2015, the Ellen MacArthur Foundation (2017) found that, globally, 73% of discarded textile materials were disposed in a landfill or incinerated, and less than 1% were recycled into new clothing. According to their study, global clothing production has approximately doubled in the past 15 years, but the average number of times a garment is worn has decreased by 36%. In the EU, consumption of clothing has increased by 40% from 1996 to 2012 (EEA 2014). To deal with this situation, upcoming EU legislation will require textile reuse or recycling.

Our goal is to compare the GWP impacts of five different ownership and end-of-life scenarios for jeans that relate to typical CE principles in the textile sector. In table 1, we present the main working mechanisms (functional logics) on which developed scenarios are based together with related ways to reduce GWP.

BASE represents current practice in which a user buys a new pair of jeans and, after a certain use period of traditional ownership, disposes them to a waste-to-energy facility. REDUCE and REUSE represent existing CE practices that are already widely used. In the REDUCE scenario user extends the time they use a purchased pair of jeans. In this scenario, environmental benefits are assumed to follow from avoidance of primary manufacturing of a product. In the REUSE scenario a used pair of jeans is sold in a secondhand shop for a new user. Through slowing the consumption cycle, this type of ownership chaining is assumed to produce environmental benefits by reduction of primary manufacturing of a product. RECYCLE and SHARE are new CE innovations. In the RECYCLE scenario used jeans are industrially transformed into new textile materials, which can be used to create new products. In this scenario, environmental benefits are assumed to follow from decreased use of primary raw materials (in this case, cotton). In

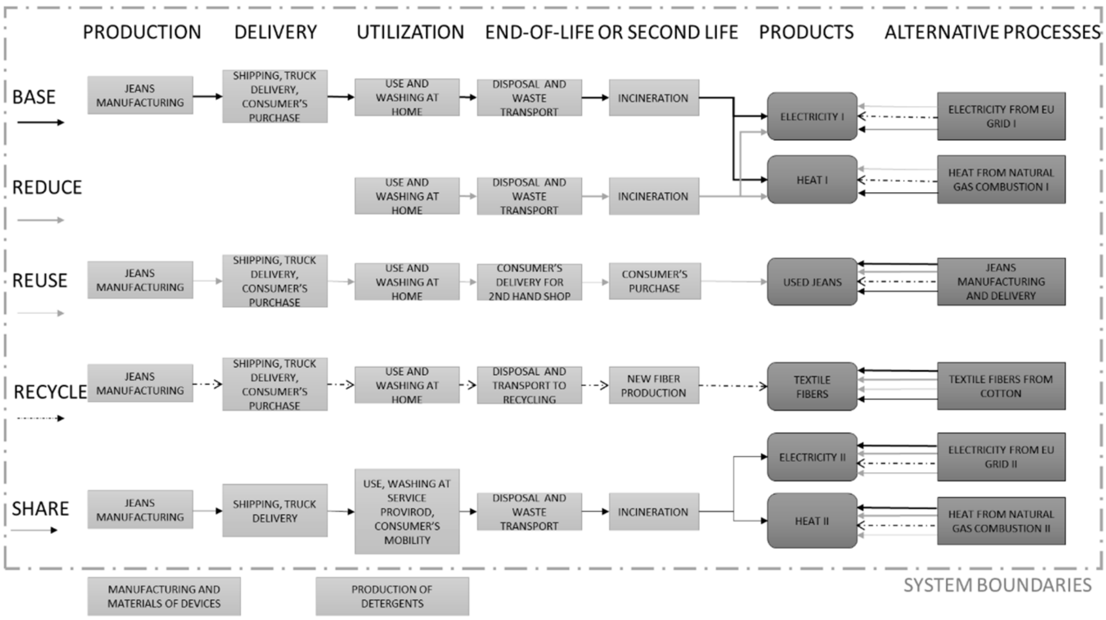

Figure 1. System expansion comparison of BASE, REDUCE, REUSE, RECYCLE and SHARE scenarios as well as system boundaries for different ownership and end-of-life scenarios for jeans.

Table 1. Studied scenarios, their functional logics, and assumed ways to reduce GWP.

	End-of-life scenarios	**Ownership scenarios**
Current practice	**BASE**	
Functional logic	Energy use through incineration	Traditional ownership
Existing CE practices	**REDUCE**	**REUSE**
Functional logic	Extended use	Ownership chaining
Assumed GWP reduction	Avoidance of primary manufacturing of a product	Reduction of primary manufacturing of a product
New CE innovations	**RECYCLE**	**SHARE**
Functional logic	Transformation of re-used products into new materials	Collaborative consumption
Assumed GWP reduction	Decreased use of primary raw materials	Intensification of the utility rate of a product

the SHARE scenario the same pair of jeans is leased or rented to multiple users during the product lifecycle. This scenario resembles the logic of collaborative consumption, in which environmental benefits are assumed to follow from increasing the utility rate of a product.

The developed scenarios are theoretical in that they do not describe a business model or a practice of any individual company or actor. Instead, they describe established or emerging activities that can be considered typical or particularly interesting from the CE perspective. New CE innovations—the creation of new fibers from textile waste and different product-as-service options that avoid clothing purchases—are still under development, but they have recently attracted interest among research communities and business actors (Dahlbo *et al* 2017). New business models and technologies are being developed to accelerate new CE innovations, but importantly, existing CE practices continue to be developed at the same time. This can be seen, for example, in the rise of multiple new platforms for buying and selling second-hand clothing.

To compare GWP impacts of the developed scenarios, the system expansion approach has been utilized in accordance with ISO/TR 2000. GWPs are calculated using the CML (Centrum voor Milieukunde Leiden) 2001–2016 methodology with a time horizon of 100 years. In the system expansion approach, all scenarios must produce the exact same amount of functional units (FUs) at the system level. In all scenarios, we have assumed that the user has used the pair of jeans 200 times (i.e. 200 d), and end-of-life FUs are calculated based on one pair of jeans. In this research, the FUs are, in addition to 200 uses of jeans, the electricity and heat associated with disposal, the reuse of used jeans, and produced textile fibers. In the system expansion approach, alternative processes are needed if a given scenario cannot produce all required FUs. The system expansion approach, scenarios, system boundaries, and basic assumptions are presented in figure 1.

2.2. Lifecycle inventory analysis

The GWP impact of the ownership and end-of-life scenarios for jeans is mainly determined at five positions in the value chain: manufacturing, delivery, use, end-of-life processes, and alternative production processes. Next, we introduce the inventory data and assumptions informing the analysis of activities taking place at these positions. A detailed list of the processes from the GaBi database that have been used for modeling are presented in appendix 1 and all key parameters used in modeling are presented in appendix 2.

2.2.1. Manufacturing

The manufacturing phase (i.e. cradle to factory gate in LCA terminology) covers the production of raw materials as well as the jeans into which they are made. According to EU custom statistics, Bangladesh is a leading exporter of jeans to the EU (European Commission 2020; HS codes 62034231 and 62046231). Therefore, Bangladesh is selected as the production location for modeling distribution. As there is currently no detailed information about the GWP of jeans manufacturing in Bangladesh, more general data for jeans manufacturing has been used. Periyasamy *et al* (2017) compared various jeans manufacturers and concluded that the production of one pair of 340 g jeans leads to approximately 16.2 kg CO_{2eq} from the production of fiber and fabric, including cutting, sewing, finishing, sundries, and packaging. This corresponds to 48 g CO_{2eq} g^{-1}. Periyasamy and Duraisamy (2019) calculated that the manufacturing of 570 g jeans in India leads to 25.9 kg CO_{2eq}, which corresponds to 45 g CO_{2eq} g^{-1}. For this paper, the selected average was 455 g jeans with GWP from manufacturing of 46.5 g CO_{2eq} g^{-1}.

Emissions originating in the manufacturing of jeans have been included in all scenarios except the REDUCE. An underlying assumption in the REDUCE scenario is that jeans' manufacturing has happened earlier, and therefore a decision now made by a consumer does not have impact on manufacturing emissions of previously made and purchased jeans. However, there is certain uncertainty in this assumption, because it could be possible to allocate a share of these emissions also into the REDUCE scenario.

2.2.2. Delivery

Jeans are assumed to be transported in a container ship from Bangladesh to Rotterdam in the Netherlands. Shipping is modeled with the GaBi model for the average global container ship, which uses heavy fuel oil manufactured in the EU. The total shipping distance via the Suez Canal is 14 800 km (Sea Distances 2021). The distance trucks must transport jeans from the Rotterdam port to Central European retail markets is assumed to be, on average, 500 km. Truck transportation was modeled using a Euro 5 diesel operated truck with 11.4 t payload. It is assumed that a consumer drives, on average, 2 km to purchase jeans. In the SHARE scenario, the consumer does not own jeans, but uses shared jeans. There are various sharing models, but the one used in this paper was inspired by the Finnish company Vaatepuu (Niinimäki *et al* 2018). In this model, the consumer loans a pair of jeans for a few weeks, and it is assumed that, after ten uses, the consumer returns the jeans to the sharing service provider and gets a new pair. Two kilometers of driving in a passenger car is assumed because the service is in a physical location (the meaning and significance of this assumption is further discussed in the section 3.3). However, there is high uncertainty related to this assumption because also other modes of transport, such as public transportation, are possible, and the purchase of jeans may be connected to other purchase activities. Emissions related to car use are modeled based on a 1.4 l petrol Euro 4 passenger car.

2.2.3. Use

Use of jeans, especially washing operations, leads to GWP. According to a consumer study conducted in Sweden, jeans are typically used ten times before washing, and there are 20 laundry cycles in the life cycle of jeans (Zamani *et al* 2017). The electricity consumption of laundry machines in the EU is approximately 0.16 kWh kg^{-1} but can vary from 0.12 to 0.20 kWh kg^{-1} (Gooijer and Stamminger 2016). The same number of washes and electricity consumption of washing were assumed for all scenarios no matter whether washing was done by a consumer or a sharing service provider. It is assumed to be from EU's electricity grid. Manufacturing and delivery of jeans can be avoided in REDUCE scenario because after 200 uses jeans can still be usable. In many cases there can be other reasons for discarding jeans than wear out.

2.2.4. End-of-life processes

For the end-of-life processes (i.e. incineration and recycling), jeans are assumed to be transported 100 km by a waste truck, which is modeled as a Euro 5 diesel-operated truck with a 11.4 t payload. Waste is handled at an incineration plant that produces both heat (2.54 MJ) and electricity (1.41 MJ). The plant is modeled based on a municipal incineration plant for textile waste. In the REUSE scenario, the consumer takes the jeans to a secondhand marketplace via a passenger car, with an assumed average driving distance of 2 km. The replacement rate for used jeans is assumed to be 0.5, but there is uncertainty related to this assumption (Sandin and Peters 2018). The replacement rate can be lower if jeans are already worn but also higher up to one if jeans are in a good shape. The production of new textile fibers from jeans waste is modeled using a German production plan that converts waste textiles into cotton fibers (0.346 kg). The total number of uses of jeans before

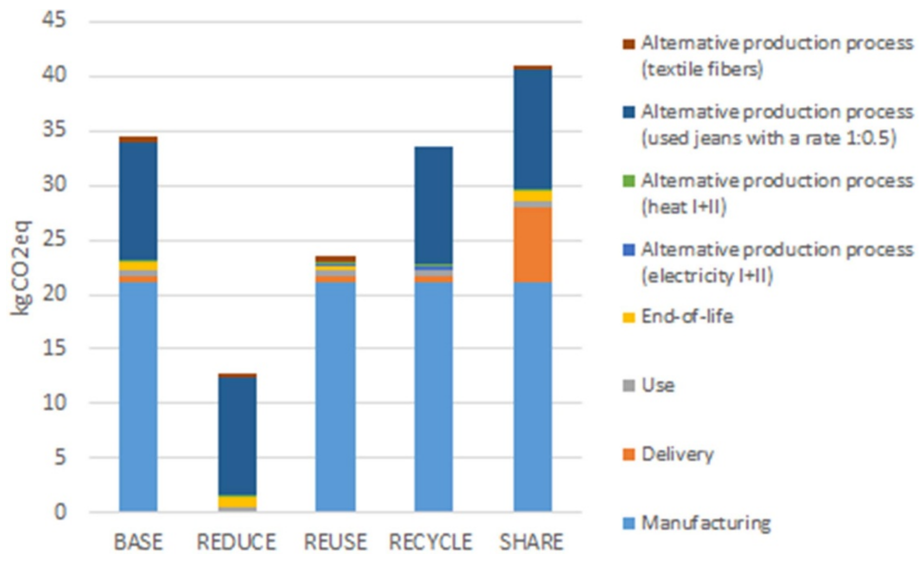

Figure 2. GWP impacts of the studied ownership and end-of-life scenarios for jeans.

disposal and incineration is assumed to be 200. All passenger car use in the end-of-life phase is modeled similarly to that in the delivery phase.

2.2.5. Alternative production processes for FUs

From a system perspective, all scenarios must produce the same amount of FUs. Therefore, also alternative production methods are needed for FUs in every scenario. Alternative electricity production (if jeans are not incinerated) is modeled based on average electricity production in the EU. Similarly, heat production is modeled based on natural gas in the EU. Jeans manufacturing and distribution is modeled similar to the way described in previous sections, in which the scenarios do not include an extended life for jeans. If jeans are not utilized for the production of new fiber, alternative fiber production is carried out with cotton. This is modeled as GaBi process for a global cotton production.

3. Results

In this section, we present the results of life cycle impact assessment. GWPs are presented separately for activities taking place in different value chain positions and the developed ownership and end-of-life scenarios of jeans. We also perform a sensitivity analysis of the results to identify the impacts of key assumptions.

3.1. GWP impacts of the studied scenarios

Figure 2 presents the GWP of the studied ownership and end-of-life scenarios for jeans. Each scenario provides for 200 uses of jeans with the exact same amounts of FUs. Therefore, each scenario includes emissions from alternative production processes. Our analysis suggests that the REDUCE scenario leads to the least GWP, followed by the REUSE scenario. It is important to note, however, that certain uncertainty relates to the assumption that no burden from the previously purchased jeans is allocated in the REDUCE scenario. If 50% of burden would have been allocated, GWP in the REDUCE would be approximately at the same level as in the REUSE scenario.

Our findings show that existing CE practices in which the lifecycles of textiles are simply extended (REDUCE and REUSE) seem to lead to significantly lower GWP impacts at the system level than utilization of new CE innovations, which utilize emerging leasing options (SHARE) or new ways of producing re-usable fibers from textile waste (RECYCLE). From this, it logically follows that, to reduce overall GWP from the textile value chain, clothes and all other textiles should be kept in use long as possible.

3.2. Rebound dynamics of the studied scenarios

Our findings encourage consideration of the role of the rebound effect in efforts aimed at advancement of CE. Based on our analysis, the studied CE innovations come with a high risk of rebound. In the RECYCLE scenario, production of raw materials is avoided, but production of cotton generates relatively low emissions, whereas the industrial stage in which re-used clothes are turned into new materials produces a high level of emissions. This leads to a situation in which the overall value chain provides only moderate GWP reduction compared to the energy use for textiles. Similarly, the SHARE scenario succeeds in intensifying the utility rate of a product, but there is a high risk that it would increase consumers' mobility, which would translate into high extra emissions. In this case, overall total GWP would be even higher than in the BASE scenario.

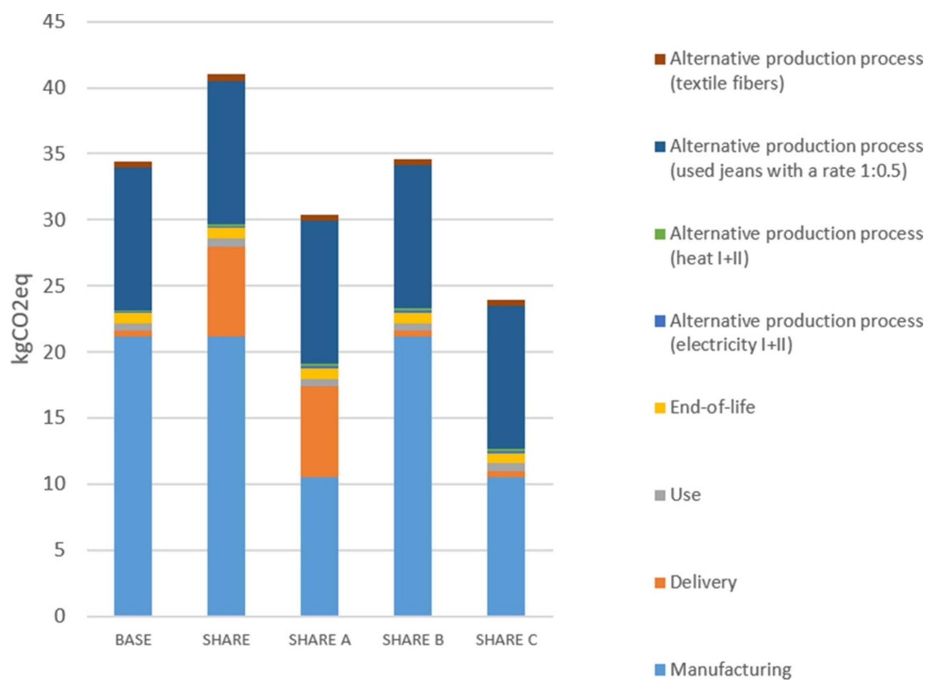

Figure 3. Sensitivity analysis for the SHARE scenario.

Smaller rebound risks are associated with existing CE practices. Both the REDUCE and REUSE scenarios carry the risk that the extended use stage of clothes would not replace primary production or slow their consumption cycles as assumed. Extended use does not automatically mean that the user's collection of clothes remains the same, nor does reselling automatically lead to increased use time; it may be that people buy extra clothes from second-hand shops simply because of their cheap price. This type of activity does not have any effect on primary production.

3.3. Sensitivity analysis

Our findings align with those of EcoForum (2015), which show that the majority of cotton textile GWP impacts originate during the manufacturing process, in which cotton is transformed into textiles. In other words, cotton production has significantly lower GWP impacts than manufacturing of textiles. There are, however, also different findings. Wang *et al* (2015), for example, have found that cotton production and fabric production from cotton have approximately equal contributions to GWP. It seems that the key assumptions behind analyses explains, at least partly, the differences in results.

Our results show that, from a systems perspective, the highest GWP is related to jeans manufacturing, which also influences the GWP of alternative production processes. Analytical uncertainties are highest in the SHARE scenario, in which the distribution phase has a high GWP and other processes have marginal GWPs. To illustrate the role of key assumptions, we carried out a sensitivity analysis for the SHARE scenario (figure 3).

Renting or leasing services can provide high-quality jeans to customers and ensure that jeans are not unexpectedly discarded, for example, due to rapid fashion changes. At the same time, there are significant uncertainties related to use times and the logistical arrangement of these services.

The SHARE A scenario shows the GWP when jeans are used 400 times instead of 200 times, as expected in SHARE. This change leads to significantly lower GWP. Another uncertainty is related to delivery. The SHARE B scenario assumes that a user picks up jeans via low-carbon modes of transportation, such as a bicycle, which would result as GWP reduction through avoided emissions from mobility. The SHARE C scenario illustrates the combined effect of the SHARE A and SHARE B scenarios. In sum, it can be said that if uses can be doubled and delivery can be arranged without impacts to GWP, then the SHARE C scenario can reach approximately the same level of GWP as the REUSE scenario. This could be reached if sharing services are located close to consumers and good quality jeans are used to ensure extended use cycle.

4. Discussion and conclusions

While discussion about the CE is welcome and may provide fresh ideas regarding the most serious problems of our time, it is important to raise awareness about the potential rebound effects that might be associated with solutions that perfectly align with the general principles of CE. Luckily, such a discussion is emerging (Figge and Thorpe 2019, Millar *et al* 2019). It is also very important to pay attention to behavioral changes that need to be coupled with new CE-related practices. Similarly important is to note that many of the expected sustainability impacts of CE remain at the theoretical level (Korhonen *et al* 2018), which is why we urgently need more detailed research on the assumed and unexpected implications of diverse CE strategies (Haupt *et al* 2016).

4.1. Rebound risk in the advancement of CE

Our findings show that, while innovative solutions can improve sustainability in certain value chain positions, they can also maintain significant rebound effects at the system level. In the textile industry, massive over-production is a system-level problem that cannot be tackled only with the development of more efficient recycling options for end-of-use products. Currently, reduction of the total amount of products in the circuit is the most efficient way to steer the sector toward more sustainable practices. REDUCE and REUSE strategies are the most practical for achieving such goals. Cantzler *et al* (2020) have noted that these types of strategies typically require new business models, while recycling can be more easily coupled with existing business practices.

Our study shows that to avoid negative rebound effects, new business models are not always needed. The REDUCE scenario requires only that jeans are used longer, and the REUSE scenario can be realized with existing secondhand business models. However, it is also important to note that large-scale mainstreaming of activities described in REDUCE and REUSE scenarios might face different types of challenges. For example, extended use and re-selling might not be possible if clothes simply do not last long enough. Therefore, facilitation of these types of activities might require new business models combined with production of more durable or repairable clothes, which again can result in slightly different GWP impacts than what we have modeled.

When considering whether we should prioritize the spread of existing CE practices or the development of new CE innovations, it is important to note that existing practices operate in a dynamic relationship with the new innovations that are entering businesses and people's everyday lives. Our findings suggest that, when new CE innovations are not capable of challenging existing CE practices, they may end up maintaining existing problems in the value chain. To facilitate environmental benefits at the system level, it is critical for new innovations to be insightfully combined with existing practices. For example, if the production of new raw materials from used clothes could lead to a situation in which the new products made from those materials have a special meaning for their users and make them willing to use the products for longer than other clothes, then positive sustainability outcomes could gradually start to manifest at the system level. To produce such special meaning, products made from recycled materials should be of particularly high quality.

4.2. The meaning of behavioral changes

The prevalent fast-fashion paradigm results in an abundance of cheap products in the market (Niinimäki *et al* 2020), which places individual customers in a controversial situation; for many reasons, buying long-lasting products can be much more difficult than buying non-durable products (van Loon *et al* 2017). At the same time, there is no pressure for textile industry to implement more sustainable practices if there is no growing demand for higher-quality products.

In many situations, users' capacity to change their behavior plays a key role in the systemic advancement of CE (Hazen *et al* 2017, Levänen *et al* 2018). Our results are in line with other studies (Zamami *et al* 2017, Piontek and Müller 2018, Piontek *et al* 2020) showing that the textile sector is no exception. While previous research (e.g. Farrant *et al* 2010, Sandin and Peters 2018) has stressed that from the environmental perspective use phase extension is very important, our research combines similar findings with specific CE scenarios, which allows more focused discussion about the required behavioral changes. It is important to note that in our study the role of behavior is the most critical success factor in both REDUCE and REUSE scenarios, which also provide largest GWP reductions.

It follows that, in addition to spreading existing CE practices and developing new CE innovations, more attention should be paid to customers' choices and preferences in different situations. Buying, using and disposing of clothes comprise a complicated socio-cognitive process to which we attach diverse meanings, emotions and values (Laitala 2014, Fletcher 2015). Clearly, diverse CE strategies will not achieve their potential if they are not crafted so that their implementation generates reflection among their target audience about which types of products and services are really needed in a good life (Bocken and Short 2020, Freudenreich and Schaltegger 2020). Increased information sharing is one way to stimulate such reflection. Therefore, we recommend the development of business models that couple high-quality products with information technology that helps to communicate sustainability aspects of the product as well as the importance of extending the product's use time. For many everyday products, such as textiles, repair and refurbishment services may be interesting business areas.

4.3. Limitations and areas for future research

It is important to note that our focus on the GWP impacts of cotton-based products has certain limitations. First, focusing on a clothing item made from synthetic fibers would probably have resulted in different GWP impacts due to the greater energy demand of the production process (Niinimäki *et al* 2020). Second, our research on GWP impacts has left implications for other sustainability dimensions outside the scope of our study. To understand the large variety of sustainability implications of diverse CE scenarios in the textile sector, future analyses should include impacts on water, land, biodiversity and human communities.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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Appendix 1. List of GaBi processes used in modeling

Life cycle step	Selected process from the GaBi database
Shipping	GLO: container ship (5000–200 000 dwt), distance: 14 800 km
Heavy fuel oil for ship	EU-28: heavy fuel oil at refinery
Truck transport and waste transport	GLO: truck, Euro 5, 14–20 t gross weight/11.4 t, distance: 500 km, 100 km (waste truck)
Diesel for a truck	EU-28: diesel mix at refinery
Consumer's mobility with a passenger car	GLO: car petrol, Euro 5, engine size up to 1.4 l, distance: 2 km
Gasoline for a passenger car	EU-28: gasoline mix (regular) at filling station
Electricity production	EU-28: electricity grid mix
Waste incineration	EU-28: textiles in municipal waste incineration plant
Textile recycling into fiber	DE: cotton fibers (from recycled clothes)
Alternative heat production process	EU-28: thermal energy from natural gas
Alternative fiber production process	GLO: cotton fiber (bales after ginning) Cotton Inc.

Appendix 2. List of key parameters for CE scenarios

Scenario	Production	Delivery	Utilization	End of life or second life	Products at a system level
BASE	One pair of jeans 21.2 $kgCO_{2eq}$	Shipping 14 800 km truck 500 km consumer (passenger car) 2 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1}	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
REDUCE	No production and delivery: use of earlier purchased jeans which are still intact after 200 uses	—	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1}	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
REUSE	One pair of jeans 21.2 $kgCO_{2eq}$	Shipping 14 800 km truck 500 km consumer (passenger car) 2 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1}	Consumer (passenger car) 2 km additional 100 uses after secondhand shop	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
RECYCLE	One pair of jeans 21.2 $kgCO_{2eq}$	Shipping 14 800 km truck 500 km consumer (passenger car) 2 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1}	Truck 100 km recycling to new fibers	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
SHARE	One pair of jeans 21.2 $kgCO_{2eq}$	Shipping 14 800 km truck 500 km consumer (passenger car) 20 times 2 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1} (by service provider)	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]

(Continued.)

(Continued.)

Scenario	Production	Delivery	Utilization	End of life or second life	Products at a system level
SHARE A	One pair of jeans 21.2 $kgCO_{2eq}$, but due to extended total use (400 uses) only 50% of manufacturing is allocated for FU.	Shipping 14 800 km truck 500 km consumer (passenger car) 20 times 2 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1} (by service provider)	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
SHARE B	One pair of jeans 21.2 $kgCO_{2eq}$	Shipping 14 800 km truck 500 km	FU: 200 uses 20 washes washing machine electricity 0.16 kWh kg^{-1} (by service provider)	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]
SHARE C	One pair of jeans 21.2 $kgCO_{2eq}$, but due to extended total use (400 uses) only 50% of manufacturing is allocated for FU.	Shipping 14 800 km truck 500 km	FU: 200 uses 20 washes washing machine consumption 0.16 kWh kg^{-1} (by service provider)	Truck 100 km incineration	Electricity 2.1 MJ[a] heat 3.8 MJ[a] textile fibers 0.35 kg[b] jeans 0.5 pcs[c]

[a] If jeans are not incinerated for electricity and heat in the end-of-life stage, alternative energy production is needed. Alternative electricity production is assumed to happen with an average electricity production mix in the EU and alternative heat production with natural gas.

[b] Production of cotton fibers are needed in all scenarios except in the RECYCLE, in which fibers are made from end-of-life stage jeans.

[c] In the REUSE scenario, old jeans for re-use are provided via a secondhand shop. In all other scenarios, emissions originating in the manufacturing of new jeans are included in the modeling. It is assumed that emissions of one new pair of jeans are equal to those of two pairs of used jeans. Therefore, 50% of jeans' manufacturing emissions are allocated for alternative processes.

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