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Resource efficiency of consumables – Life cycle assessment of incontinence products

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ABSTRACT

Circular economy is presented as a sustainable alternative to the take-make-waste society. The discourse on circular economy emphasizes the role of durable products, while consumable products are less in focus, although resources efficiency is needed for all types of products. This paper aims to contribute knowledge on resource efficient measures that are possible to implement for consumables and to evaluate their resource efficiency potential by means of a case study on incontinence products using life cycle assessment. Four possible measures were identified that can be implemented at different stages of the value-chain, to increase their resource efficiency. The study was delimited to measures possible to implement using current technology. The measures were: recycling of waste generated in production, increasing the share of bio-based material in the product, shifting to a partly reusable product system and more effective use of products through customization to user's needs. Effective use of products through customization led to at least 20% decrease in environmental impact with no trade-offs between studied impact categories. However, when looking at global warming potential only, the partly reusable product system was found to decrease environmental impact with more than 50% compared to a corresponding disposable product. Moreover, many resource efficient measures were identified as being possible to implement for consumables, and in the case of incontinence products a combination of measures was possible.

1. Introduction

Global material usage is growing continuously and is strongly linked to increased consumption rather than increased population (UNEP, 2017). Consequently, resource efficiency and sustainability are prominent on the political agenda (UNEP, 2017). Resource efficiency (RE) can be defined as using the Earth´s limited resources in a sustainable manner while minimising impacts on the environment (EC, 2017c). It implies creating more with less and delivering greater value with less input. One manifestation of resource efficiency is the concept of Circular Economy (CE), which is "an economic system that replaces the "end-of-life" concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes…with the aim to accomplish sustainable development" (Kirchherr et al., 2017).

The current CE discourse emphasises the role of durable products, suggesting longevity strategies such as robust design and restorative measures, e.g. maintenance, repair and remanufacturing, along with strategies to use products to their full potential through sharing schemes (e.g. EMF (2013); (Stahel and Clift, 2016)). There seems to be less emphasis on consumables, although these products also need to be resource-efficient. Consumables are products capable of being consumed; they may be destroyed, dissipated, wasted or spent (Locke, 1913). Examples of such products are food, hygiene articles, paper and similar consumer goods, as well as disposable products.

One example of consumable products that will still be used in the future is incontinence products. Every country in the world is experiencing growth in the number and proportion of elderly in their population (OECD, 2017; United Nations, 2015) with associated increased need for healthcare and healthcare products, such as incontinence products. Incontinence is the inability to control the bladder or intestine, which leads to leakage, and is considered to be a large public health problem. For people living in elderly homes in Sweden, more than 50% are incontinent (Peeker and Samuelsson, 2015).

Strategies for consumables in the circular economy presented by one of its leading proponents, the Ellen MacArthur Foundation (EMF), are redesign of products to increase the content of bio-based material and redesign to remove toxic constituents for safe recycling (EMF, 2013). EMF acknowledges that some short-lived products could be redesigned to become more durable or transformed into service systems,

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but emphasises the strategy of increasing bio-based material use. Others present improvements in the production phase, e.g. to reduce production waste and recycle scrap materials, as well as redesign to reduce material usage during all life cycle stages, as important strategies for consumer goods (IVA, 2016). Moreover, recycling and usage of waste materials in production are examples of circular strategies, regardless of durable or consumable product (e.g. EC (2017a)).

Clearly, there are many possible strategies and measures for RE for consumables as well as durables. Typologies have been presented e.g. by Bocken et al. (2016); Potting et al. (2017) and Böckin et al. (2018). More knowledge is however needed to understand what measures are suitable and possible to implement for different types of products in general, and consumable products in particular, and what their RE implications are.

In line with Böckin et al. (2018), we here consider RE to mean the same function fulfilled using less natural resources, in terms of both resource use and environmental impacts. We use the framework of Böckin et al. (2018) to identify measures possible to apply to incontinence products and then evaluate their RE potential by means of life cycle assessment (LCA). LCA was used since it can reveal burden-shifting between life cycle stages as well as between types of environmental impacts (e.g. (Haupt and Zschokke, 2017; Kjaer et al., 2018)) and enables examination of total amount of resources used and emissions generated from a product system. The identified measures were all such as could be implemented using existing technology and thus were without radical technological innovation.

The aim of the paper is to contribute knowledge about measures for RE that are possible to implement for consumables and evaluate their potential for resource efficiency, using a case study of incontinence products to answer the following questions:

- Which resource efficient measures, possible to implement in a short-term perspective using existing technology, are effective for reducing use of natural resources and environmental impact for incontinence products?
- Which measures have the largest potential for resource efficiency?

2. Background

2.1. Resource efficiency of healthcare products

A number of studies have investigated the environmental and resource implications for reusable versus disposable products in the healthcare sector. For example, Sørensen and Wenzel (2014) investigated the environmental implications of different bedpans (for toileting bedridden patients) and found the disposable option to be slightly better due to the high energy demand for washing reusable bedpans. Helgestrand et al. (2011), compared disposable and reusable hygiene sheets and found results strongly dependant on the number of sheets required per user and year and the impacts from washing. Kümmerer et al. (1996) compared reusable and disposable laparotomy pads (tamponades in operative medicine) and found the disposable option had a higher consumption of natural resources.

A number of studies have investigated the environmental impact of baby diapers. Cordella et al. (2015) investigated the evolution of disposable diapers in Europe and carried out LCA to identify key areas for improvement. They found that lighter products and the introduction of superabsorbent polymers historically improved the environmental impact of diapers. Careful selection of low impact materials at the design stage, while ensuring functionality, was found to potentially decrease life cycle impacts further, whereas malfunctioning products risked increased diaper consumption (Cordella et al., 2015). In a study by O´Brien et al. (2009) three different diapers were compared by LCA in an Australian context. Two reusable diapers, one home-washed and one commercially washed, and one disposable diaper were compared. The home-washed reusable nappies were found to have the lowest environmental impact if washed in a water-efficient washing machine in cold water and line-dried. Mirabella et al. (2013) investigated a completely bio-based diaper for resource efficiency. The authors concluded that biopolymers in diapers could make them environmentally preferable to standard diapers but stressed the risk of shifting burdens between types of environmental impact. Lastly, Ng et al. (2013) critically reviewed seven LCA studies on diapers from different countries and concluded that single-use diapers create more solid waste during their life cycle, while reusable cloth diapers create more impacts during their use phase due to washing activities.

Fewer studies have specifically investigated the environmental impacts of incontinence products. One example by Muthu et al. (2013) evaluated the environmental performance of two disposable and two reusable incontinence products and found that reusable pants with disposable insert generated the lowest footprints (disregarding impact from the use-phase, since this was excluded from the study).

It is clear that no consensus exists about whether, and under which circumstances, a reusable product is superior to a single-use product in the healthcare sector. Moreover, to our knowledge, there have been no previous studies comparing a variety of different resource-efficient measures.

2.2. Description of the incontinence product system

The main function of an incontinence product is to absorb urine, and in some cases restrain faeces, while providing comfort and dignity to the users by keeping them dry and avoiding odour. Due to a large variability in the degree of incontinence, a range of products exist with different absorbing capacities for different situations and needs. For instance, a user able to walk and to change the product has different needs than a bedridden user, who requires assistance from nursing staff to apply and remove the product. Further, the products come in different sizes to fit different body types.

The materials and components in incontinence products are similar but vary with respect to the amount used. The top layer, closest to the skin, is nonwoven material (often polypropylene-based), to let fluids through (Nikola, 2017). Thereafter, there is either a layer of a cellulosic material, called curly fibre, or a nonwoven material to facilitate even fluid distribution to the absorbing core. The absorbing core consists of a mixture of superabsorbent polymer (SAP) and cellulosic fluff material. A blocking layer (a nonwoven material and a breathable polypropylene-based film) is placed underneath, making sure no fluids can pass through. In addition, glues and elastics are used to keep the product together and in place (Nikola, 2017). Fig. 1 shows a simplified flowchart of the incontinence product system from cradle to grave, including the most important parts of the life cycle. For a more detailed flowchart see Figure S1.1. in the Supplementary material.

In this study, a number of specific products were investigated:

- Disposable Pants – an all-in-one product that functions both as underwear and an absorbing product. Used for low to medium incontinence problems.
- Pants – a reusable and washable fixation pant in which an absorbing insert is placed.
- Light Pads – an insert pad used in combination with regular underwear or the Pants product. Used for low to medium incontinence.
- Shaped Pads – an insert pad used in combination with regular underwear or the Pants product. Used for low to high degree incontinence.
- All-in-one – used for high degrees of incontinence. The product is designed as an open-styled diaper with tape straps to close the product and ensure it stays in place.

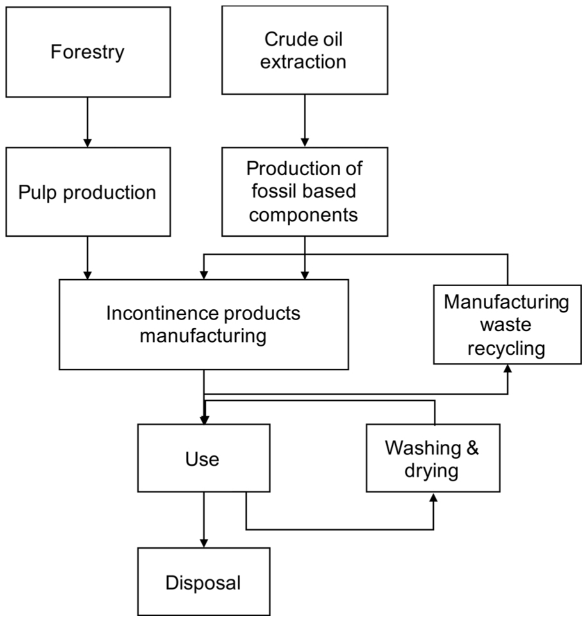

Fig. 1. Simplified flowchart of the incontinence product life cycle.

3. Method

3.1. Research approach

The framework with measures for RE (Böckin et al., 2018) were applied to the incontinence product system to identify measures relevant to analyse. The framework uses a product-chain perspective to identify physical RE measures that can be applied over a product's lifecycle. The measures are divided into three overarching categories, defined by where in the lifecycle the measures can be implemented. The first category comprises improvements in the *extraction and production phase*, e.g. more efficient material usage by reducing production waste. The second category aims at increasing the efficiency in the *use phase of products*, through *extending their use* e.g. by prolonging the technical lifespan, or through *effective and efficient use*. The third category comprises measures regarding *post-use*, e.g. recycling and incineration with energy recovery.

However, not all measures were deemed suitable for incontinence products and possible to implement using existing technology and were accordingly excluded from the study. The aspects considered when assessing suitability were the characteristics and function of the product, and the needs of the users and healthcare system. For example, measures such as recycling the materials in used products or bringing a used product back to use were not investigated as this is not feasible with current technology and infrastructure, and due to the nature of the product. The measures considered suitable were then applied to a case company's existing products and assessed quantitatively with LCA. Literature, interviews with personnel at the case company and a study visit to an elderly home facilitated study design and data collection. Lastly, sensitivity analyses were conducted for several parameters identified to have inherent uncertainties and to be important for the results.

3.2. Investigated measures

3.2.1. Reduce losses in production

The first measure investigated was to reduce losses in production by recycling of waste material generated in manufacturing (see Fig. 1). By recycling the manufacturing waste, the raw material demand may be decreased.

To investigate the RE potential of this measure, two alternatives for managing the waste generated in manufacturing were compared:

1 Material recycling

Production waste from the manufacturing of incontinence products was separated into material fractions, which were assumed to be recycled back to production.

2 Incineration

For comparison, the waste from manufacturing of incontinence products was assumed to be transported to a waste incineration plant.

3.2.2. Changed material composition

The second measure was to change the material composition in the products to a higher share of renewable material. Two products with a different share of renewable material, but the same absorption capacity and function, were compared. This strategy thus addresses the role of product design and its effect on upstream material production (see Fig. 1).

3.2.3. Multiple use - reuse parts of product

The third measure consisted of making part of the product, the pant fixating the absorbing part of the product, reusable. The absorbent part, however, was still a disposable product. To investigate the role of having a partly reusable product system, reusable Pants with the absorbing Light Pads insert were compared with the Disposable Pants product. The two product systems were considered comparable since they both have the same absorption capacity.

3.2.4. Effective use through customization

The fourth measure aimed to improve use of products through customization for individual patients, their incontinence patterns and other needs. Similar to the previous measure, this measure addressed the use phase, but instead focused on effectiveness.

Customization of incontinence products for individual patients requires that the incontinence pattern is somehow mapped. Different measurement techniques can be used to identify incontinence patterns, e.g. by sensors or weighing. This study used data from an elderly home where a weighing method was used. The incontinence products were weighed before and after use for three days and the times of product change and toilet visits were documented. In this way, incontinence severity was recorded (O'Donnell et al., 1990). In addition, the patients' waist size was measured. The data, together with an assessment of the general health status of the patient was used to identify suitable products with regard to absorption capacity, size and comfort, for each patient. The measurement programme was set up, and the recommendations made, by the product manufacturer.

The environmental impact of the products used on the ward was compared for two cases:

- before measurements were conducted, meaning that what products were used was based on nursing staff experience and routines, and
- after measurements and implementation of product recommendations based on these.

3.3. Scope and system boundaries

The selected measures were applied at different system levels. For this reason, it was not possible to use the same functional unit for all four different strategies. *Hygiene function of one absorbent product with medium absorption capacity of medium size*, was used as a functional unit for the three first measures. *Hygiene function for one day at the studied ward in an elderly home* was used for fourth measure.

The study included current technologies, both in terms of design solutions and manufacturing methods, and therefore the investigated

Table 1
Overview of materials, their function and production location together with source of used data on material production.

Material	Main resources	Function	Product	Production location	Source
Fluff	Pulp tissue	Absorb fluids in the core	All	US	supplier-specific
SAP	Acrylic acid polymer	Absorb fluids in the core	All	Japan	Helgestrand et al. (2011)
Curly fibre	Pulp tissue with adhesives	Fast urine transport to absorbing core	Light Pads	US	supplier-specific
Nonwoven	Polypropylene	Top layer	All	Sweden, Germany, Czech Republic	Helgestrand et al. (2011)
BLC Nonwoven	Polypropylene	Hydrophobic nonwoven which ensures body waste is kept in the core	Disposable Pants	Czech Republic	Helgestrand et al. (2011) and Roos et al. (2015)
ALD Nonwoven	Polypropylene/ polyethylene	Fast urine transport to absorbing core	Disposable Pants	Italy	Helgestrand et al. (2011)
Breathable back-sheet	Polypropylene	Breathable material furthest away from skin that prevents urine leakage	All	Germany	Helgestrand et al. (2011)
Glue	Naphtha, paraffin	Glue parts together	All	Germany, Sweden	Helgestrand et al. (2011)
Elastic leg	Synthetic rubber	Elastic leakage barrier	Shaped Pads, All-in-One	Luxembourg	Roos et al. (2015)
Elastic film	Synthetic rubber, polypropylene	Waistband	Disposable Pants, All-in-One	Wales	Roos et al. (2015)
Elastic	Elastane	Overall elastic parts	Disposable Pants	Northern Ireland	Roos et al. (2015)
Bag	Polyethylene	Bag	All	Sweden	Hischier (2007a)
Corrugated cardboard box	Corrugated cardboard	Box	All	Sweden	Hischier (2007b)

measures could be realized today. Data collection for the investigated cases was done during the spring of 2017 in collaboration with the manufacturer. Site specific production data, collected in 2016, was used for the assembly of the products as well as for the production of several constituent materials. In other cases, data for material production was collected from literature, see Table 1. Moreover, background data was sourced from the Ecoinvent 3.3 LCI database (Ecoinvent, 2016) and the study was carried out using OpenLCA software (Ciroth, 2007).

The LCA used an attributional approach. For this reason, average data, rather than marginal, was used. In the background data, modelled with Ecoinvent datasets, allocation was based on economic value, using product prices collected from various literature sources (e.g. UN Comtrade for many different products) or prices calculated based on the value of the products entering production (Moreno Ruiz et al., 2016). Since part of the products consists of renewable materials, both uptake of carbon during growth of biomass and release of biogenic carbon at the end-of-life were accounted for.

The manufacturing of incontinence products took place in Aneby, Sweden, whereas the fixation pants were produced in Denmark. The distribution, use and waste management of the products was assumed to take place in Sweden. Usage was assumed to take place in Linköping, since this was the location of the elderly home. This location was used to determine transport distances. Waste management was modelled with generic Swedish end-of-life treatment data. The production of material components and raw materials were mainly outside of Sweden. To as large an extent as possible, relevant national electricity mixes and other national specific processes were used. For more details, see Supplementary material S1.

In the end-of-life stage, system expansion was applied to avoid allocation. The used products and the bags the products were delivered in were incinerated and the generated electricity and heat were assumed to replace the need for producing heat for district heating and electricity to the national grid. In addition, the packaging boxes were assumed to be recycled. This material was assumed to replace the need for producing new corrugated cardboard. Average data was used for all cases of system expansion.

3.3.1. Impact assessment

When analysing the results, first weighting was used in order to filter the results and select those midpoint indicators which contributed the most to over-all weighted results. Further analysis and conclusions was then based entirely on the selected midpoint indicators. A similar approach was first used by Tillman et al. (1998). More recently, the use of single score results has been recommended by Kägi et al. (2015), if supported by midpoint and inventory information.

By using two weighting methods that differ as much as possible from one another (they employ different bases for valuation, geographical scopes, time horizons etc.) complementary perspectives were used for the filtering. The methods used were the ReCiPe single score method with a hierarchist approach (Hischier et al., 2010), which bases its weighting on preferences stated by a panel of LCA experts as described by Itsubo et al. (2015), and the Environmental Protection Strategies (EPS) method (Steen, 1999), which uses monetary valuation. The two weighting methods were used in combination to select the most relevant midpoint impact categories. In the first stage of the analysis, the weighting, the full set of midpoint indicators included in the used impact assessment package (Ecoinvent 3.3) and which lead up the weighted results, was used. After selecting the most important midpoint impact categories, all analysis and further conclusions was based on those.

All characterization and weighting factors were taken from the Ecoinvent 3.3 impact assessment method package from 2016, in which ReCiPe version 2008 (Goedkoop et al., 2009) and EPS version 2000 (Steen, 1999) are included (Ecoinvent, 2017). The midpoint indicator values were calculated using the ReCiPe impact assessment method with hierarchist perspective. A more recent version of ReCiPe from

Table 2
Material composition expressed in grams of Shaped Pads, Light Pads, Disposable Pants M and Pants M.

Material	Shaped Pads (g)	Light Pads (g)	Disposable Pants M (g)	Pants M (g)
Fluff	23	27	36	
Curly fibre	5	5		
SAP	9	7	15	
Breathable back-sheet	3	2	2	
Nonwoven	2	2	16	
Glue	0.5	0.5	2	
Elastic rubber/foam	0.01	0.2	1	
Tape /release paper	1.2	0.5		
Elastane				11
Polyamide				0.5
Total	44	44	72	11.5

2016 (Huijbregts et al., 2016) was, for practical reasons, not used since it was not included in the most recent Ecoinvent impact assessment method package (Bourgault, 2017).

4. Inventory

Key inventory data for the analysed incontinence products are presented below, along with descriptions of material source, manufacturing operations, and use and disposal activities. Inventory data specific for the different investigated measures are also presented. For more detailed inventory data, see Supplementary material S1.

4.1. Materials

The same materials are used in all investigated products, but in varying amounts and proportions (as specified by the manufacturer, although this information cannot be revealed for confidentiality reasons). Data on material production was taken from literature as specified in Table 1, with the exception of fluff and curly fiber, for which production data came from a specific supplier.

4.2. Manufacturing

Manufacturing of incontinence products starts with cutting pulp into smaller pieces, followed by de-fiberizing through air pressure. The fluff is then mixed with the SAP to create the absorbing mixture. The different materials are assembled using glue or welding. Edges are then cut and trimmed. During cutting and trimming some waste is generated, mainly consisting of nonwoven, fluff and SAP. The manufacturing process also generates waste in the form of products discarded for quality reasons.

The fixating pants are produced by a supplier in Denmark and consist of elastane and polyamide that is produced in Germany and Poland, respectively.

4.3. Distribution and use

The manufactured products, placed in bags and boxes, are transported to a distribution storage in Gothenburg, Sweden and subsequently to the end user. In this study, users are assumed to be located in or close to Linköping, Sweden.

The Pants are assumed to be used and consequently washed and dried 20 times before disposal. Washing is assumed to be in a regular residential washing machine with a normal load at 60 degrees, followed by drying in a normal-loaded tumble dryer. Following Roos et al. (2015), normal load is taken as 59% of the full capacity. Data for the washing processes were taken from Stamminger (2007) and Roos et al. (2015), and the data for tumble drying from Roos et al. (2015).

4.4. End of life phase

After using the incontinence products and Pants, the products, bags and boxes are disposed of and transported 7.3 km to the local waste management plant, where the products and bags are incinerated for energy recovery, and boxes are recycled.

4.5. Data for investigated measures

4.5.1. Reduce losses in production

The manufacturing of incontinence products generates waste; for the Disposable Pants approximately 7% of the incoming material ends up as waste. In this investigation two alternatives for handling the production waste were assessed.

In the first alternative, the waste was assumed to be recycled at the manufacturing site. The waste was sorted into smaller fractions and separated to enable recycling of SAP, fluff and plastic-based materials. The recycling process was estimated to consume 100 kW h of electricity per 100 kg waste, with a material efficiency of 98% (according to the manufacturer). The remaining 2% were assumed to be incinerated together with fractions that could not be recycled at a waste management plant at a distance of 54 km.

A second alternative evaluated the impact of not recycling any material, but instead incinerating the total waste volumes from production. The waste was incinerated at the same plant as previously.

The current practice is to send manufacturing waste to Germany where fluff, SAP and all fossil-based components are material recycled. SAP and fluff are used to produce absorbing material for baby diapers, and plastics are used to produce plastic pallets, thus avoided production of new materials are considered. The rest of the waste fractions are incinerated with energy recovery. The current practice was evaluated in a sensitivity analysis for this measure, but considered as normal practice in the assessment of the other measures.

4.5.2. Change material composition

In the second measure, two products with similar function but different material composition were compared (see Table 2). Shaped Pads contain slightly more fossil-based materials (SAP, breathable back-sheet and nonwoven) whereas Light Pads contain more cellulose material (fluff and curly fibre).

4.5.3. Multiple use - reuse parts of products

In the third measure, the reusable product Pants medium (M) used together with the disposable absorbing product Light Pads were compared with the completely disposable all-in-one Disposable Pants M with the same absorption capacity as the Light Pads (see Table 2).

4.5.4. Effective use through customization

To improve the use of products, urinary leakage was measured for one ward with seven patients at an elderly home in Linköping, Sweden. The measurements allowed for recommendations on what products to use, customized to each patient. Patients had different general states of health and degrees of incontinence problems and were therefore using different incontinence products. The patients had their own rooms with bathrooms in which they had their own washing machines and driers.

5. Results

The results from the life cycle assessment for the four investigated measures are presented below. Firstly, the strategies are evaluated with the two different weighting methods, EPS and ReCiPe single score, to identify which midpoint indicators and inventory results contribute most to the results. The measures are then evaluated with regard to the selected midpoint indicators.

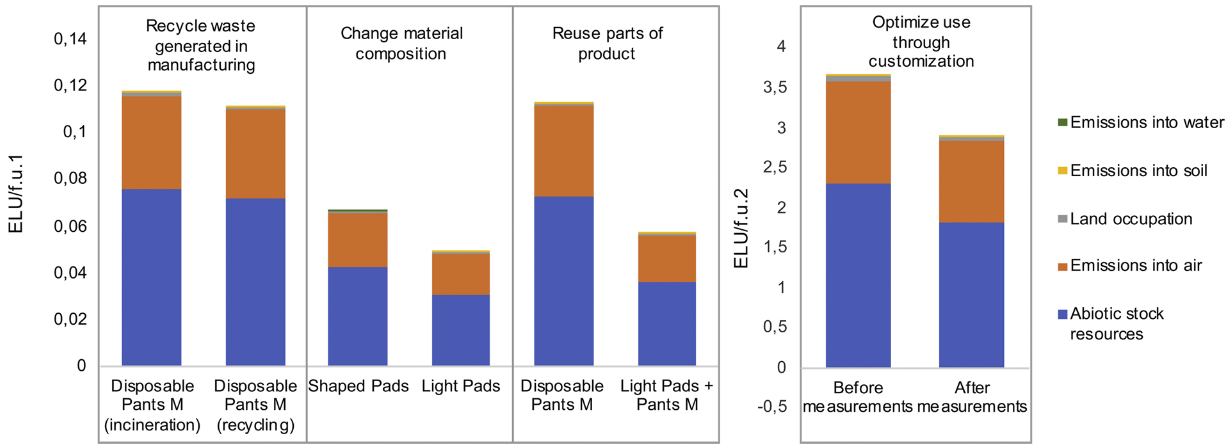

Fig. 2. EPS results for the products used in the first three investigated measures to the left (with the functional unit "hygiene function of one absorbent product") and products used in the fourth measures (effective use through customization) to the right (with the functional unit "hygiene function for one day at the studied ward in an elderly home").

5.1. Weighted result

The weighted EPS results are shown in Fig. 2. The results are dominated by abiotic stock resources and emissions to air. Natural gas and crude oil use were the main contributors to abiotic stock resources, while carbon dioxide was the dominant emission to air. Emissions to water and soil and land occupation did not influence the weighted EPS results to any noticeable extent.

Moreover, the strategy to reuse part of the product resulted in the largest potential for improvement (37% decrease in score). Changing the material composition resulted in a 26% decrease and effective use of products through customization resulted in a 21% score reduction. Recycling of production waste, however, only resulted in a 5% decrease compared to incineration.

From the EPS analysis it was concluded that the resources of greatest importance in the product lifecycles were natural gas and crude oil, with carbon dioxide the most important emission.

Similar results were obtained when applying the ReCiPe single score weighting method (see Fig. 3). The dominant midpoint impact categories are land use (classified as agricultural land occupation in the ReCiPe method, though mainly accounting for occupation of forest land), fossil depletion (dominated by crude oil and natural gas), and climate change.

ReCiPe ranks the customization strategy as the most promising, decreasing the impact by 20%. The strategy to reuse part of the product was found to be the next most promising, with an improvement potential of 17% according to ReCiPe (compared to 37% according to EPS). The improvement potential from recycling of production waste is similar to EPS, 6%, while the improvement potential from changing to a larger fraction of bio-based material is smaller, only 4% (compared to 26% with EPS). This can be explained by ReCiPe placing more weight on land use.

The ReCiPe single score method points to the same resources and impacts as the EPS method, however with the addition of land occupation. Based on the EPS results and the ReCiPe results combined, the following midpoint impact categories were selected and used for further analysis. They were calculated using the ReCiPe midpoint indicator method (Goedkoop et al., 2009) with hierarchist perspective:

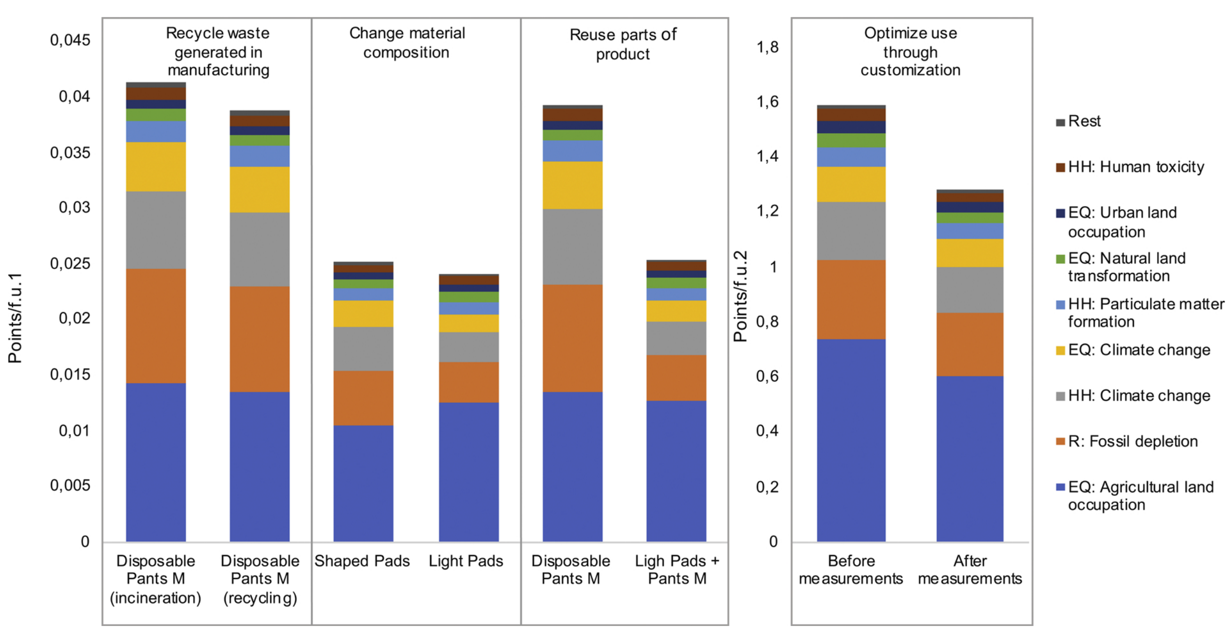

Fig. 3. ReCiPe single score results for the products used in the first three investigated measures to the left (with the functional unit "hygiene function of one absorbent product") and products used in the fourth measure (effective use through customization) to the right (with the functional unit "hygiene function for one day at the studied ward in an elderly home"). EQ is Ecosystem quality, R is Resources, and HH is Human Health.

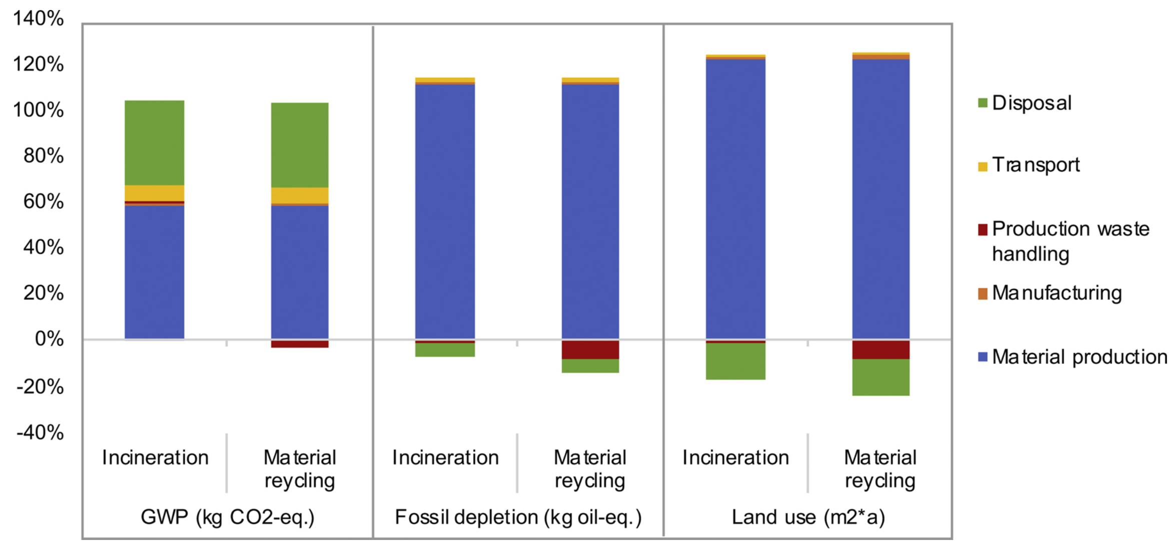

Fig. 4. Normalized results for the selected impact categories global warming potential, land use and fossil resource depletion for two different waste handling alternatives (incineration and material recycling).

- Global warming potential (kg CO_2-eq.)
- Fossil resource depletion (kg oil-eq.)
- Agricultural land use (m^2.year annual crop land)

5.2. Reduce losses in production

For the three selected impact categories, material recycling resulted in somewhat lower impact compared to incineration (see Fig. 4); 4% decrease in global warming potential, 7% decrease in fossil resource depletion and 6% decrease in land use impact. Furthermore, material production was the phase of product life cycle that contributed the most to environmental impact, whereas manufacturing contributed the least. The end-of-life phase in which the products are incinerated contributes significantly to global warming.

5.3. Change material composition

The implications of increasing the share of renewable materials in a product were investigated (see Fig. 5). A 30% lower global warming potential, a 22% lower fossil resource depletion and a 20% higher impact on land use were obtained for the product with a slightly higher share of renewable materials (Light Pads) compared to the Shaped Pads with a higher content of fossil-based materials. Thus, despite moderate changes in product composition, large changes in impact results were obtained.

5.4. Multiple use- reuse parts of product

Disposable Pants have a significantly larger impact than Light Pads with Pants M (see Fig. 6). For global warming potential and fossil depletion, the impacts were more than twice as large for the completely disposable product, whereas the difference for land-use impact was negligible.

It is also worth noting that the contribution from washing and drying of the reusable pants was only around 1% of the whole life cycle impact.

5.5. Effective use through customization

Table 3 shows the results of the leakage measurements at the elderly home and the recommendations made for the patients, based on these. For most users, the absorption level could be decreased. For some of the

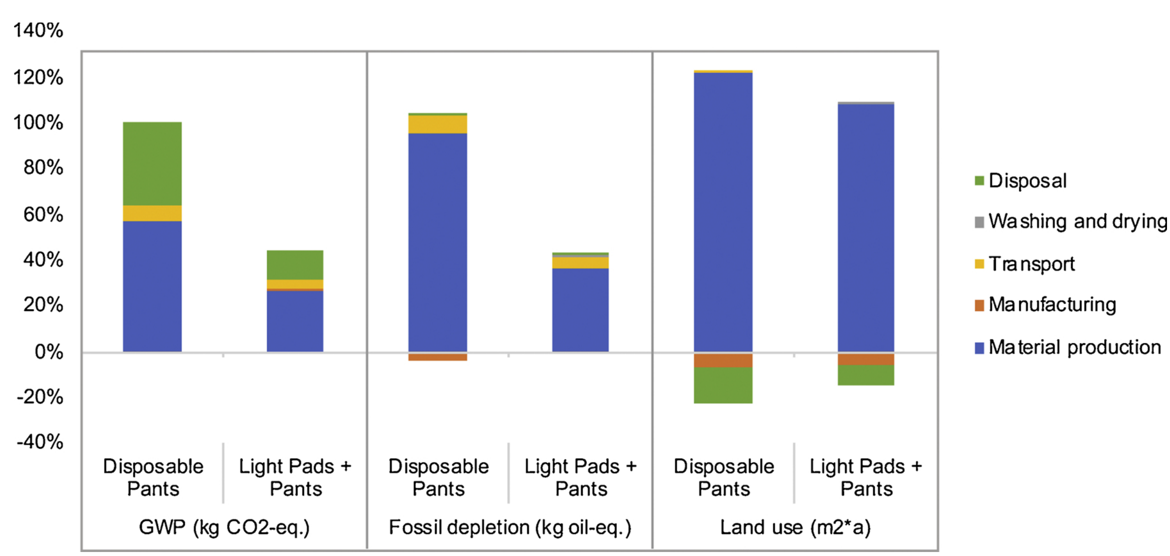

Fig. 5. Normalized impact assessment results for Shaped Pads and Light Pads.

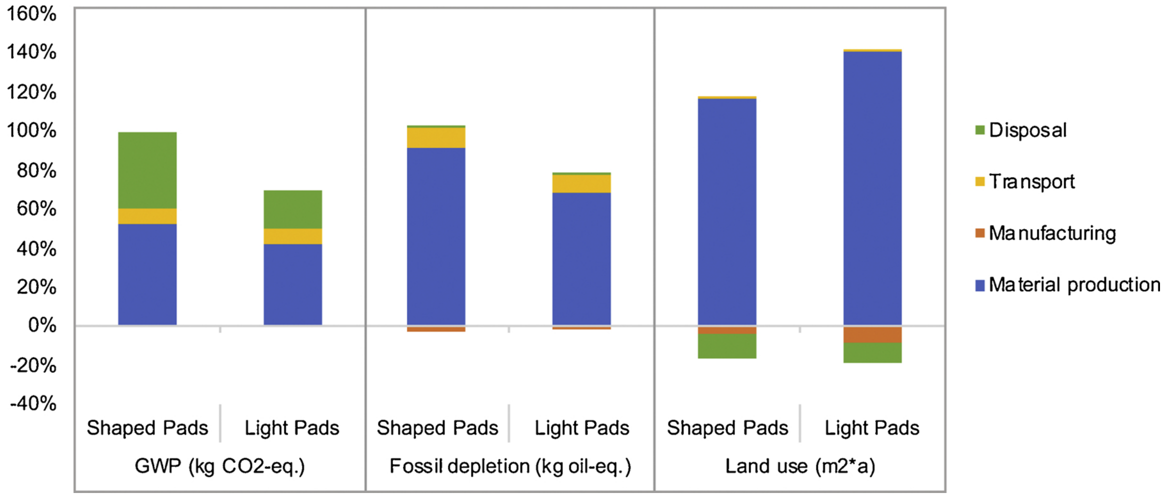

Fig. 6. Normalized impact assessment results for Disposable Pants M and Light Pads with one use of Pants M.

patients, the size of product could be reduced. New products were recommended for all patients except one. For one patient, a new product type was recommended, i.e. patient 1, from All-In-One 10 XL to Shaped Pads 8 during the night.

The results from the impact assessment are presented in Fig. 7. A decrease in environmental impact after implementation of the recommendations can be seen. Changing from the current products used on the ward to the new recommended products resulted in a 23% decrease in global warming potential, a 20% decrease in fossil depletion and a 18% decrease in land use.

6. Sensitivity analysis and discussion

6.1. Production

Material production dominated environmental impact in all investigated cases, with 60–90% of the impact deriving from material production processes, depending on case and impact category. This means that any strategy that reduces material use improves the environmental performance. Moreover, the materials that are used most in the products, such as SAP, fluff and nonwoven, are also those that contribute the most to the environmental impact. SAP was the dominating material with regard to global warming and fossil depletion. This is in line with previous studies investigating the environmental impact from incontinence products and diapers, e.g. (Cordella et al., 2015; Muthu et al., 2013; Ng et al., 2013). In addition to SAP, the use of nonwoven, which is produced from fossil-based polypropylene, leads to a large contribution to GWP and fossil depletion. Fluff, on the other hand, is produced from wood and consequently impacts land use instead.

One way of decreasing material use is by recycling production waste. In our assessment, we assumed the material to be recycled internally. However, there are barriers to internal recycling for incontinence products, which on the European market are classified as medical equipment, requiring materials to be traceable and of high purity (EC, 2017b). For this reason, production waste from incontinence products is often recycled externally, to the less demanding baby diaper market. To control for impact of transport and recycling with a less clean electricity mix, a sensitivity analysis was conducted in which waste recycling took place in Germany, meaning additional transportation and more fossil-based electricity. The shift to more fossil-based electricity resulted in a slight increase of GWP. The additional transport, however, did not influence the result to any noticeable extent (see Figure S2.2 in Supplementary material S2).

6.2. Change material composition

Another strategy to decrease the impact from material production is to change from fossil-based to more renewable-based materials in the products. As shown in section 5.3, with a higher share of fossil-based materials, Shaped Pads generated higher impacts on global warming and fossil resource depletion, whereas Light Pads, which contain more wood-based materials, generated higher land-use impact. Such trade-offs between impact types, and hence risk of burden-shifting, when

Table 3
Presents the mean mass leakage for every changed product (night and day) together with the products used before and after the measuring period, where the numbers indicate the absorption capacity.

Patient	Day / Night	Mass leakage (g)	Products before initiating measurements	Products recommended after measurements
1	Day	411	Shaped Pads 10, Pants XL	Shaped Pads 8, Pants L
	Night	430	All-In-One 10XL	Shaped Pads 8, Pants L
2	Day	154	All-In-One 10M	All-In-One 8M
	Night	622	All-In-One 10M	All-In-One 8M
3	Day	461	Shaped Pads 10, Pants L	Shaped Pads 9, Pants L
	Night	1014	All-In-One 10XL	All-In-One 10L
4	Day	74	Disposable Pants 5L	Disposable Pants 3M
	Night	36	Disposable Pants 5L	Disposable Pants 3M
5	Day	206	Shaped Pads 10, Pants L	Shaped Pads 8, Pants L
	Night	454	All-In-One 10XL	All-In-One 8L
6	Day	284	Shaped Pads 9, Pants M	Shaped Pads 7, Pants M
	Night	371	Shaped Pads 10, Pants M	Shaped Pads10, Pants M
7	Day	366	Shaped Pads 10, Pants L	Shaped Pads10, Pants L
	Night	1619	All-In-One 10XL	All-In-One 10XL

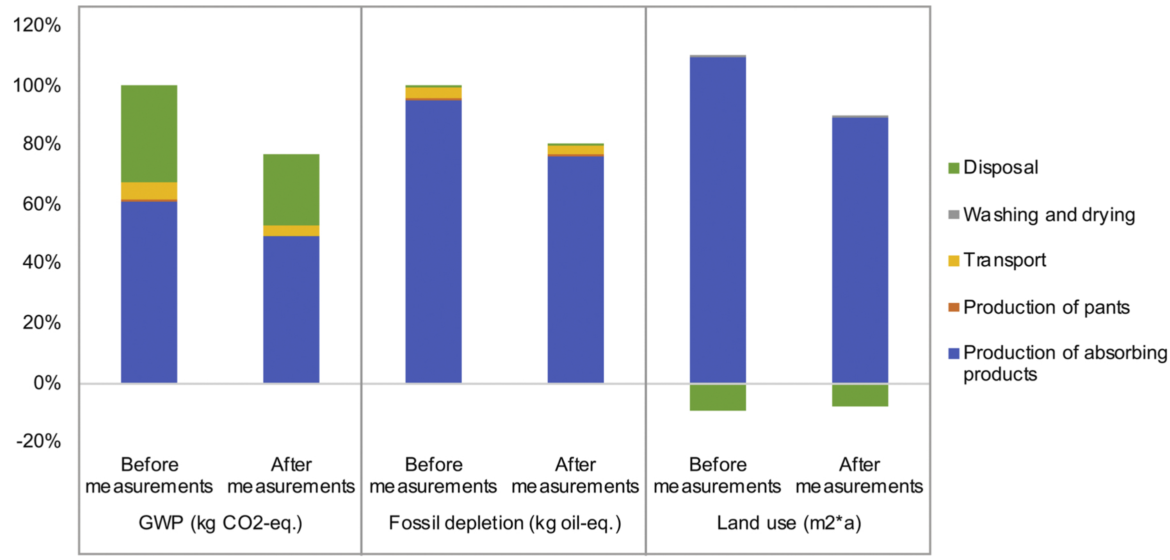

Fig. 7. Impact assessment results for life cycle of the products used before initiating the measurement and after initiating the measurements.

moving to more bio-based diapers was previously identified by Mirabella et al. (2013).

However, it is not completely clear what an increased land use could mean and what effects it could lead to. There are many impacts that LCA does not capture well that are linked to land use, for example impact on biodiversity and soil quality. These are all difficult to measure and impact assessment methodologies for such impacts is still under development. Variability due to spatial differences and differences between different types of ecosystems is also considerable (Koellner et al., 2013).

SAP and fluff are also only partly interchangeable as absorbent materials. The benefit of SAP is its ability to absorb many hundreds of times its own weight while having a very high retention. Fluff can also absorb large quantities but has low retention. Similar to a sponge, absorbed volumes can easily be released when pressure is applied. The benefit of fluff is instead that it can absorb liquids quickly, whereas SAP absorbs slowly.

6.3. Multiple use- reuse parts of product

We compared the partly reusable product system Pants with Light Pads with the all-in-one Disposable Pants product. Making the product partly reusable was the measure that resulted in the greatest decrease in global warming potential and fossil-resource depletion (nearly 60%). However, there were several uncertainties in this comparison, which were controlled for through sensitivity analysis.

For a fair comparison the product systems compared must have an equal function. For this reason, products with the same absorption level according to the manufacturer's scale were chosen. However, when comparing the material composition of the products it is clear that the material content of the absorbing cores of the products differed substantially, see Table S2.2 in Supplementary material S2. Absorption capacity according to the ISO method also differed substantially. (The ISO method measures the total absorption capacity irrespective of absorption rate (ISO 11948, 1996ISO 11948, 1996)).

As a sensitivity analysis, Pants M and Light Pads, with one higher absorption level than the base case, were compared with Disposable Pants M with one level lower absorption level than the base case. These products have a more similar material composition and ISO absorption capacity (see Table S2.2 in Supplementary material S2). The all-in-one product Disposable Pants still generated distinctively larger impacts on both global warming and fossil resource depletion (see Figure S2.3 in Supplementary material S2) in line with the findings in the base scenario. This strengthens the conclusion that single-use pants generate substantially larger impacts on global warming potential and fossil resource depletion than reusable pants with an absorbing insert. However, in regard to land-use impact, the choice does not matter.

Another uncertainty related to the reuse strategy was the environmental impact from washing activities. In contrast to previous studies (Helgestrand et al., 2011; Ng et al., 2013; Sørensen and Wenzel, 2014), we found the impact from washing and drying to be almost negligible. Merely 1% of the total global warming potential of the Light Pads and Pants product system originated from washing and drying. In order to verify the robustness of this result, sensitivity analyses were performed.

The results were firstly tested for a different electricity production mix. As a worst case the electricity for washing and drying was changed to a mix of 100% lignite instead of the essentially fossil-free Swedish mix. This did not substantially increase GWP (see Fig. 8).

To verify the role of energy use for washing and drying, the results were then tested for different loads in the machines, from regular (3.2 kg laundry) to a low load of 1 kg. This did not influence the life cycle result to a noticeable extent, since modern washing machines automatically adjust to different loads (Stamminger, 2007) (see Fig. 8). Washing and drying in an industrial washing and drying facility, with more efficient processes, was also tested, without noticeable effects on the result (see Fig. 8). However, as a worst case, when it was assumed that the pants were washed and dried as the only garment in the machines the impact increased significantly and changed the order of ranking between the compared alternatives (see Fig. 8).

6.4. Effective use through customization

This measure was found to be the one with the largest potential to improve resource efficiency when considering improvements in all the three impact categories (land use, global warming potential and fossil depletion). An overall decrease of 20% for the impact categories was obtained by effective use of products through customization.

It should be stressed that this measure was exemplified with a case study of a real ward with seven patients living at an elderly home. These do not represent the mean value of all patients or users and the results from this assessment do not have any statistical significance. However, according to the personnel at the elderly home, the group of patients studied were believed to be a good average representation of patients at elderly homes.

From semi-structured interviews with employees at the elderly home and the incontinence product manufacturer some qualitative

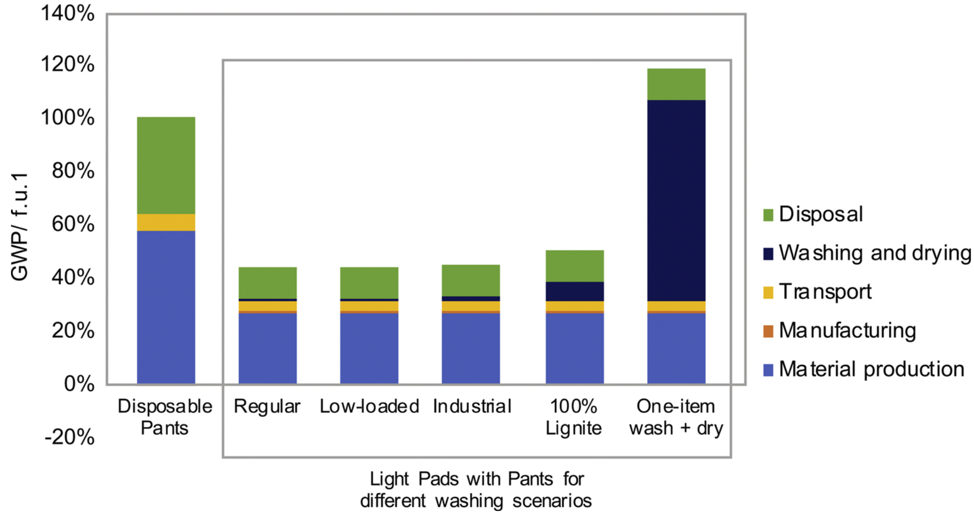

Fig. 8. Washing and drying sensitivity analysis for the Pants used with Light pads normalized to the GWP impacts from the use of Disposable Pants.

observations were made:

- When incontinence measurements are made, they generally reveal that at least two absorption levels too high are used by patients.
- Patients with large body size are often believed to have more severe incontinence than patients with smaller body size, which leads to larger patients often being assigned products with too high absorption capacity.
- Decisions regarding what incontinence product to use are commonly based on medical charts together with the nursing staff's experience, developed from years of trial and error.
- The validity of recommendations based on measurements is transient, since the health state of patient changes over time.

These experiences were largely confirmed by the measurements. As can be seen in Table 3, five of the seven patients could decrease their absorption capacity two levels. For some of the patients a decrease of the size of the products from XL to L was recommended.

Lastly, worth noting is that it is possible to combine the four measures, although evaluation of this possibility was left outside the scope of the study. However, the measures *effective use through customization* and *reuse parts of products* cannot be combined freely. All users have different incontinence degrees and general health status and therefore a two-piece product solution might not be suitable for every user.

7. Conclusions

A general conclusion is that since environmental impact was dominated by material production for all three selected impact categories, all means that decrease the use of material reduces environmental impact.

The measure aimed at effective use through customization had no trade-offs between the selected impact categories. This measure led to at least a 20% decrease in environmental impact for all three impact categories.

However, reuse of parts of the product resulted in the largest environmental savings in terms of global warming potential and fossil resource depletion. A 50–60% decrease could be obtained when moving from a completely single-use product to a partly multiple-use product. In order to reuse the product, the pants needed to be washed and dried between uses, which was not found to contribute significantly to the environmental impact. Even when the electricity mix for washing and drying was changed to a worst case (100% lignite), the Disposable Pants still had a higher impact.

Changing the material in the products from more fossil-based to more renewable-based resulted in a decrease in GWP and fossil depletion. However, this came at the price of increased land use.

Recycling of scrap and waste material from production reduced environmental impact in all three selected categories by around 5%. The results were not sensitive to the location of the material recycling but a more fossil-based electricity production mix for the recycling process made recycling of scrap material somewhat less beneficial.

An important observation in the case study was that all four investigated RE measures could be combined. For example, recycling of production waste does not hinder the design of a product with more renewable materials or the use of a partly reusable product. Indeed, applying one measure does not need to exclude implementation of the others.

In conclusion, this case study showed considerable possibilities to lower the resource consumption and environmental impact for a consumable such as incontinence products through a number of different measures, which furthermore proved to be largely possible to combine with one another.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.12.026.

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